Optimal and Precautionary Management of the German Bight in the Presence of Thresholds

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List of Abbreviations

CBA	Cost Benefit Analysis
CEA	Cost Effectiveness Analysis
CFP	Common Fisheries Policy
CPUE	Catch Per Unit Effort
EU	European Union
EEZ	Exclusive Economic Zone
FTE	Full Time Equivalent
IBTS	International Bottom Trawl Survey
ICES	International Council for the Exploration of the Sea
MPA	Marine Protected Area
MSFD	Marine Strategy Framework Directive
MSP	Marine Spatial Planning
MSY	Maximum Sustainable Yield
SES	Social Ecological System
SSB	Spawning Stock Biomass
SST	Sea Surface Temperature
STECF	Scientific, Technical and Economic Committee for Fisheries
TAC	Total Allowable Catch
TP	Tipping Point

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Chapter 1

Introduction

The vastness of the ocean is perhaps indicative of the amount of information necessary to successfully manage fisheries, while the opaqueness and depth of its waters hint that this information is not always available. Yet, management is necessary, if future generations or even our own generation are to continue to profit from the bounties it provides. Gone are the centuries, where fish stocks were assumed to be functionally endless and management of the fish stocks unnecessary (Appleby et al., 2013). In European waters, the erstwhile practice of allowing open-access was replaced by a system of quotas (European Commission, 2018). However, how high the quotas should be remains a contentious issue. From an economist's perspective, this is a question of how to trade off the economic benefits of harvesting today against those that will be possible in the future if the stock is maintained. In order to judge the impacts of harvests today on the opportunity of future harvests, the relationship between the two needs to be known. However, a significant uncertainty exists in this relationship. Marine ecosystems are subject to three sources of uncertainty: i) random shocks, ii) uncertainty in parameters and states of nature, and iii) structural uncertainty (Charles, 1998).

Of these, structural uncertainty is of particular importance. Structural uncertainty refers to the basic understanding of the system. This includes the ways in which different species interact with each other and their stock-growth relationships, how fishing gear interacts with the ecosystem, and how human behaviour shapes fishing pressure. In the context of this thesis, structural uncertainty can be understood as the question of which relationships to include in a model of the system and what shape these relationships have. For the shape of the relationships, it is especially important whether they contain a threshold effect, i.e. a tipping point or bifurcation. How much of the real world interactions can be omitted in the name of parsimonious modelling before the model results become irrelevant to reality, and are the real world interactions fully known in the first place? Omitting relevant relationships may cause unforeseen consequences. For example, Quaas and Requate (2013) show how omitting consumer preferences in demand may cause a sequential overharvesting of fish stocks, even when these would independently be considered stable. Hence, if the underlying model is misspecified, the best intentioned management may fail in maintaining the ecosystem stock and the fishery.

A key issue in managing an ecosystem is the presence of tipping points[1]. A system with a tipping point is characterised by multiple stable regimes. If historical data lies entirely within a single one of these regimes, a model describing the system dynamics in the historical data may be constructed without the tipping point. Such a model that is validated for a certain regime, but which does not include the tipping point, consequently will yield incorrect results in ranges where tipping would occur. In this case, the model would predict a smooth response between drivers, such as fishing pressure, and the stock status, giving the illusion that any overharvesting can be compensated by future reductions in fishing pressure, allowing stocks to recover. However, if the system has a tipping point, overharvesting may lead to a persistent collapse, where stocks will not recover even with a complete ban on fishing activity. There are multiple examples of tipping points being crossed in marine systems, where a later recovery of the stock did not occur or was very slow. Neuenhoff et al. (2019) describe the collapse of cod stocks in the Southern Gulf of St. Lawrence, on the Canadian Atlantic coast, which continued to decline even after a closure of fisheries, due to a change in the ecosystem composition. The regime shifts in species composition of the North Sea ecosystem, including the German Bight investigated in this thesis, are likely to be irreversible (Sguotti et al., 2022). This further highlights the importance of structural uncertainty in managing a fishery and the marine ecosystem.

In addition to the uncertainties within the ecosystem, the coupling of an economic system in the form of the fishing industry and households interacting on the market for fish products introduces a further set of relationships fraught with uncertainty. The combined system is also referred to as a socio-ecological system (SES). It is in this context that I investigate optimal and precautionary management approaches for the German Bight in the presence of thresholds or tipping points. To ensure a well posed problem, I focus my investigation on the the small scale coastal fishing fleets that mainly operate within the German Bight. These fleets operate as a multi-species fishery with inseparable harvests of various species. The two most important species, plaice (*Pleuronectes platessa*) and sole

[1] A tipping point is caused by the crossing of a threshold in one or more drivers of the system. The crossing of the threshold is associated with an abrupt and often irreversible change in the state of the system. This is also called a regime shift or threshold effect in the chapters below.

(*Solea solea*), are chosen for analysis. Plaice makes up a large proportion of total catches by weight, while sole makes up a large proportion of revenue. These fisheries operate under the European quota based fisheries policy. In order to properly account for the inter-dependencies and feedback effects that govern this system I develop a bio-economic model that includes key properties of the system, including threshold effects in stock dynamics. The model is based on those found in the literature but extended to include simultaneous catch properties of the plaice and sole fisheries as well as policy options.

With this dissertation, my aim is to answer the following questions:

- Which interactions are present between managed species in a multi-species fishery and what are the consequences of these interactions for management?
- What are the vulnerabilities of a fishing industry to changes in social and ecological drivers especially in the context of an interconnected socio-ecological system?
- What thresholds are present in the socio-ecological system and what are their consequences for management?

By answering the first of these questions, I address the need for a better understanding of the structural uncertainty of the socio-ecological system made up of fish stocks, fishers, and households. I investigate whether it is reasonable to omit certain types of interaction in the modelling of fish stocks and fisheries, or if such an omission would cause a deviation of system dynamics. With the second question I highlight that management of a fishery while focusing solely on optimising household welfare or persistence of ecosystem stocks may have consequences for the fishing industry and associated socio-cultural well-being in the affected communities. The answer of the third question is entwined with the first two. I investigate which tipping points exist in the socio-ecological system of the North Sea fisheries and their consequences for management.

Thesis Outline

I begin with an overview of the study area and the actors and ecosystem within it. This is followed by the development of a bio-economic model with the aim to reflect the key dynamics present in the socio-ecological system. Using the model a novel framework for the assessment of vulnerability is presented and applied in the context of the current management approach using quotas. This thesis culminates with the derivation of optimal harvest levels, their determinants and implications.

Chapter 2 introduces the concept of the socio-ecological system (SES). SES are used to describe the interconnectedness of human activities with an ecosystem. In particular, this chapter presents the results of a targeted literature review on the empirical assessments of the vulnerability of an SES to tipping points.

Chapter 3 gives an overview of the history of the coastal fishery targeting mainly plaice and sole in the North Sea and the challenges faced due to climate change. Climate change causes changes in the spatial distribution of fish stocks due to a changing temperature gradient in the North Sea as well as changes in the productivity of the stocks. This in turn has consequences for the ecosystem and socio-ecological system the stocks are a part of. This chapter describes the challenges these changes pose for the fishery in relation to the fisheries adaptive capacity.

As shown in the previous chapters, fisheries in the North Sea are generally multi-species fisheries, with inseparable simultaneous harvests of multiple species. However, in much of the economic literature modelling fisheries, it is assumed that each stock can be harvested independently. In **Chapter 4** I seek to answer the question of what consequences this simplification has for the derived dynamics of the coupled system of stock dynamics and market driven harvests.

In **Chapter 5** the vulnerability concept is applied to the bio-economic model. As the definitions of vulnerability in the SES context found in the literature are vague, sometimes conflicting and generally not satisfactory, as described in Chapter 2, a novel set of analytically sound definitions for sensitivity, adaptive capacity and vulnerability are developed. The developed framework is then applied to the bio-economic model to determine the vulnerability of fishers to various drives.

The impact of the three types of interaction introduced in Chapter 4 on optimal harvest quantities is investigated in **Chapter 6**. Furthermore, their importance in the design of total allowable catch and quantity tax based management is investigated.

Finally, in **Chapter 7** I discuss the lessons learned and how they can be applied to improve management of marine ecosystems in general and in the German Bight in particular. I further consider possible extensions and limitations of the presented research.

Chapter 2

Socio-Ecological Vulnerabilities to Tipping Points: A review

Abstract: Sustainability in the provision of ecosystem services requires understanding of the vulnerability of social-ecological systems (SES) to tipping points (TPs). Assessing SES vulnerability to abrupt ecosystem state changes remains challenging, however, because frameworks do not operationally link ecological, socio-economic and cultural elements of the SES. We conducted a targeted literature review on empirical assessments of SES and TPs in the marine realm and their use in ecosystem-based management. Our results revealed a plurality of terminologies, definitions and concepts that hampers practical operationalisation of these concepts. Furthermore, we found a striking lack of socio-cultural aspects in SES vulnerability assessments, possibly because of a lack of involvement of stakeholders and interest groups. We propose guiding principles for assessing vulnerability to TPs that build on participative approaches and prioritise the connectivity between SES components by raccounting for component linkages, cascading effects and feedback processes.
Keywords: Ecosystem-based management, socio-ecological systems, tipping points, stakeholders, transdisciplinary research, vulnerability assessments

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This chapter consists of the paper "Socio-Ecological Vulnerability to Tipping Points: A Review of Empirical Approaches and their Use for Marine Management" published in Science of The Total Environment by Lauerburg, Diekmann, Blanz, Gee, Held, Kannen, Möllmann, Probst, Rambo, Cormier, and Stelzenmüller (2019)

2.1 Introduction

Abrupt and unexpected ecosystem state changes are increasingly likely to occur under the cumulative anthropogenic pressures and the expected effects of climate change (Conversi et al., 2010; Möllmann et al., 2015). These so-called regime shifts have been documented globally for different marine ecosystems (e.g. Reid et al. (2001); Möllmann and Diekmann (2012); Beaugrand et al. (2015) and might be associated with thresholds, which are commonly defined as regions in which a small change in pressures cause disproportionately large, abrupt changes in system properties, whether in single species or populations, entire ecosystems, climate or human society (Scheffer et al., 2001; Beisner et al., 2003; Samhouri et al., 2010). These thresholds are also often referred to as tipping points (TPs) (e.g. McClanahan et al. (2011)). Acceleration is caused by positive feedbacks driving the system to a new state (van Nes et al. (2016); see glossary in Box 2.1). The term 'tipping point' was originally introduced by social scientists describing a phenomenon in the context of racial segregation (Wolf, 1963). Regime shift research in the early 2000s defined TP as a point in time or an ecosystem state that is marked by a sudden turn to a different state (Box 2.1).

Since then the term gained further popularity in many disciplines, with a variety of synonyms and definitions being used that, nevertheless lack a unified taxonomy (Milkoreit et al., 2018). Abrupt changes in ecosystem state result in changes of ecosystem functioning and the provision of ecosystem services (van Nes et al., 2016), implying that in the event of an ecological regime shift, economic and societal impacts are also likely. Such cascading effects thus represent a change in the functioning of the socio-ecological system (SES) which depends on the provision of ecosystem services.

Ecosystem-based management (EBM) should acknowledge the complexity of socio-ecological systems and account for the ecological, economic and social effects of management measures (Katsanevakis et al., 2011; Piet et al., 2019). Therefore, management processes should prepare for regime shifts not only from an ecological perspective, but need to be adapted and redefined holistically in the context of associated social and economic interdependencies (Redman et al., 2004; Folke et al., 2004; Ingeman et al., 2019). The influence of ecological TP on SES and the practical implications for ecosystem-based management are yet to be understood (Collins et al., 2011; Link and Browman, 2017; Milkoreit et al., 2018; Berrouet et al., 2018). Thus a key question is how SES respond to

Infobox 2.1 Glossary

Tipping points can be described as thresholds of localised effects, including ecological, socio-cultural or economic system properties. They occur when small changes in pressures induce large, abrupt changes in system properties, whether in single species or populations, entire ecosystems, climate or human society. Acceleration is caused by positive feedback driving the system to a new state (van Nes et al., 2016).

Social-ecological systems (SES) are coupled systems of nature and humans, acknowledging people as part of and not apart from nature (Berkes and Folke, 2000).

SES research aims to integrate both ecological research, focusing on the cross-scale dynamics of ecosystems, and social research, targeting organizations, institutions, and social practices.

Vulnerability: The affinity of a system to changes, determined by both, the exposure to external stresses and shocks and the intrinsic factors that determine the systems' resilience (Renaud et al., 2010; Chapin et al., 2010; Walker et al., 2010; Halpern et al., 2012; Cormier et al., 2013; Stelzenmüller et al., 2015).

Resilience: The susceptibility and overall (adaptive and coping) capacity of a system, determined by intrinsic factors to absorb perturbations from disturbances and reorganise by retaining essentially the same function and structure without crossing a tipping point (Bohle, 2001; Carpenter et al., 2001; Folke et al., 2004; Walker and Meyers, 2004; Walker et al., 2010).

Susceptibility: Defines the predisposition and likelihood of a system to suffer harm from a specified disturbance when exposed to it (Birkmann, 2007).

Coping Capacity: The ability of a SES to manage and overcome adverse effects of a given threat or disturbance by using available skills and resources on a short-term basis (Birkmann, 2007; Field et al., 2012).

Adaptive Capacity: The properties of a SES, including available attributes and resources that enable the SES to respond and adapt to disturbances on a medium term basis (Birkmann, 2007; Field et al., 2012).

endogenous and exogenous drivers of change (Walker et al., 2010; Berrouet et al., 2018). For instance, the risk that ecological collapse is followed by social-economic collapse has been documented for fisheries dependent communities (Serrao-Neumann et al., 2016). Such cascading events underline the importance of understanding the linkages and dynamics of SES to develop risk mitigation strategies for the sustainable use of resources. A prerequisite for the development of such risk mitigation strategies is sound understanding of the vulnerability (Berrouet et al., 2018) of SES to ecological TP. Although the value of vulnerability concepts for decision-making has been recognised, key principles or good practice guidance for their actual use in marine resource management are currently lacking (Foley et al., 2015). Here we provide results of a comprehensive review of marine case studies on the actual use of SES frameworks in combination with TP theory in marine EBM. We review the available literature based on standardised assessment criteria addressing key questions such as (i) How are SES defined and assessed?; (ii) What is 'tipping' in the SES and are there potential cascading effects within the SES?; (iii) Is the vulnerability of the SES addressed and if yes, how?; and (iv) Have the results been used for decision making? Finally, we synthesise the implications of our results and suggest guiding principles as basis for the operationalisation of SES frameworks and their adoption in management processes.

2.2 Defining Socio-Ecological Systems and their Vulnerability to Tipping Points

A standardised review process requires an a priori definition of concepts and terminology around TPs in SES. A SES comprises numerous components that are related to the provision of ecosystem services and is composed of three sub-systems (spheres) (Fig. 1). These subsystems are in turn determined by the resources that contribute to the flux of ecosystem services. In fisheries, the resource (target species) of a fishing fleet determines the state and dynamics of the components of the socio-economic subsystems. The ecological sub-system refers to the exploited population and its interaction with the environment. The cultural subsystem represents e.g. the fishing communities and the traditions that have evolved in relation to the fished resource and how they influence the behaviour of fishers. The economic subsystem represents e.g. the choices made by fishers and consumers, determining the market prices of the fished commodity depending on production costs such as fishing material or the fuel price for ships involved in harvesting the resource. All three spheres of the SES are connected to each other via linkages that depend on individual system properties. In the fisheries example the ecological sub-system might be connected to the socio-cultural sphere via the installation of marine protected areas in response to societal demands for nature conservation. The economic sphere might be connected to the ecological sphere via the number of people that are employed in the fishing sector, which in turn is controlled by the availability of the fished resource.

The vulnerability of SES to TPs results from an interaction of the vulnerability of three spheres of the economic, the ecological and the socio-cultural sub-system. Vulnerability is a function of the exposure to a specified threat, the susceptibility of the sub-system to a specified TP and the system's overall capacity (including coping and adaptive capacity) to respond to it. In this context the systems' resilience is determined by the internal systems' susceptibility to specified disturbances and its coping and adaptive capacity towards the given pressure. (Bohle, 2001; Birkmann, 2007; Walker et al., 2010; Johnson et al., 2016; Berrouet et al., 2018). Thus, the vulnerability of a SES reflects its general affinity to changes caused by the occurrence of TPs and is determined by both external threats and the intrinsic factors that determine the systems' resilience (Walker et al., 2010; Cormier et al., 2013; Stelzenmüller et al., 2015). (Fig. 2.1, Box 2.1).

Depending on the assumed linkages between the SES' sub-systems and the potential point of action of a TP, two settings are plausible. The first is that a TP might be present in only one sphere, which is the setting typically described in papers dealing with ecological regime shifts (e.g. Folke et al. (2004)). In our fishing example a TP in the ecological sphere might result in the loss of the fishing resource which might lead to knock-on or cascading effects in the other spheres. The loss of a resource might translate into the socio-cultural sub-system by causing the collapse of local fishing communities that were targeting that resource, which then potentially cascades into the economic sphere via the collapse of associated port logistics. Thus, the consequences of having reached a TP can result in a cascade of tipping elements across social, economic, legal and political systems (Cooper, 2013; Cormier et al., 2013; Elliott et al., 2017). The second setting is that in theory a TP might co-occur in multiple sub systems simultaneously, which would be the case if e.g. the local fishing community switches to another resource, due to, for

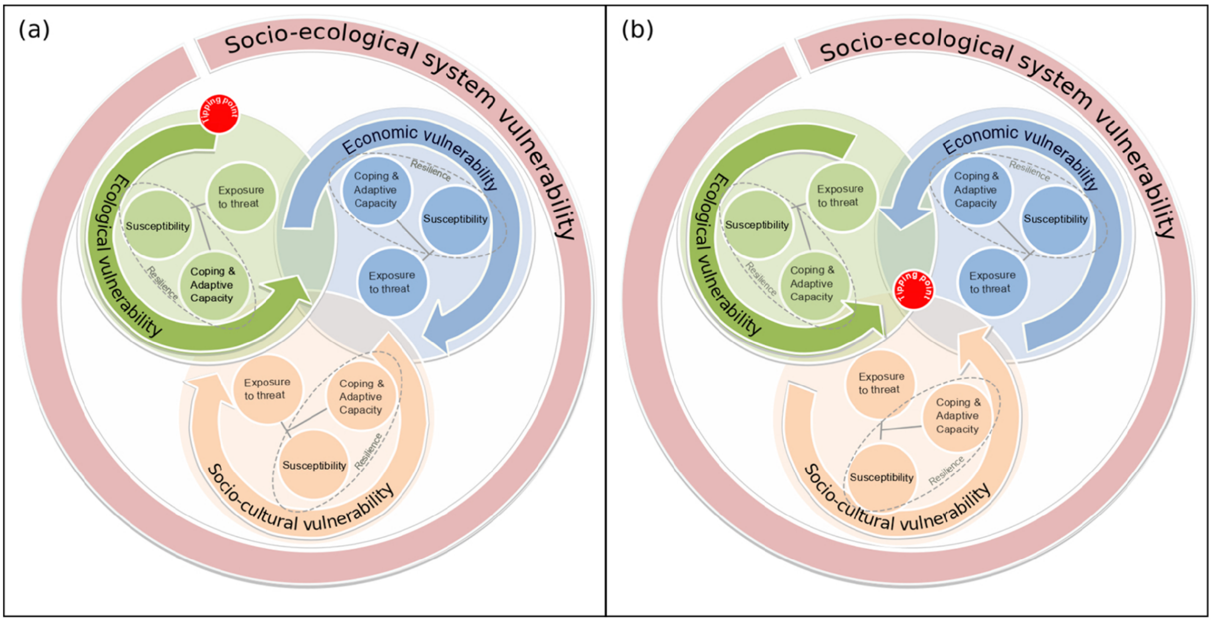


Figure 2.1: Conceptual framework of the vulnerability of a socio-ecological system (SES), the assumed connectivity of its sub-systems and the potential point of action of a tipping point (TP). Depending of the internal setting of the SES and the point of action of the TP, different scenarios are conceivable. Scenario I ('chain reaction'; panel a): The sub-systems of the SES are linearly interlinked and connected in series. The TP occurs in one sub-system, e.g. the ecological system, and affects its vulnerability to a specified disturbance. Changes in vulnerability in the directly affected ecological sub-system then reproduce in the adjacent economic sub-system due to interlinked feedback mechanisms, which in turn affects the socio-cultural sub-system. Scenario II ('chaos reaction'; panel b): All three components of the SES are interlinked in a more or less unknown way. The TP simultaneously occurs in multiple sub-systems of the SES and affects the vulnerability of the respective sub-system(s) towards a given threat in an unpredictable way. Please note that potential feedback mechanisms are not shown here.

instance, an ecological change which led to decreasing availability of the resource with a simultaneous increase in fuel prices which in turn causes that the harvest of the original resource becomes uneconomical.

2.3 Systematic Review

We identified a non-exhaustive list of six synonyms for SES and five for TP (Table 2.1) that are commonly used in the peer-reviewed literature and by experts from social, economic and ecological sciences. Using the Scopus database (www.scopus.com) we then conducted a systematic search of scientific articles published before the 16th of October 2017 with no limit back in time that made use of the concepts of SES and TP. The database itself contains publication records from 1788 onwards (Scopus Content Coverage Guide, 2017). For this, we applied all possible combinations of the keywords in the title, abstract and keywords of scientific articles in the English language, excluding articles from medical, arts and physics research journals (for search string see Table 2.3). We followed the 'Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)' approach (Moher et al., 2009) to retrieve an initial set of 211 articles for further evaluation (Fig. 2.5). Next, we screened the 211 papers in relation to their actual contents and relevance to the research questions based on titles, abstracts and keywords. 173 studies were excluded for being freshwater or terrestrial studies (N=161) or exclusively theoretical (N=12) (Figure 2.5). For the final review we selected only empirical marine case studies describing SES and a TP, resulting in 38 case studies for the detailed review (Table 2.4). Depending on the nature of the study, some publications did not explicitly use words like "coastal" or "marine" in their title, abstract or key-words (e.g. Banos-González et al. (2016); Lade and Niiranen (2017)). Therefore, it was necessary to refine the selection after the initial search which does not include key-words like "coastal" or "marine" in the search string. We assessed the retained studies with the help of 27 standardised assessment criteria (Table 2.5) derived from both the theoretical concepts of SES and TP and the research questions addressed here. They comprised not only contextual aspects such as case study location or scale, but also a description of the nature and complexity of the SES, assessment of SES vulnerability, relevant data sources, methods used or the nature

Table 2.1: Synonyms used for SES and TP in the peer reviewed literature extracted from the Scopus data base (https://www.scopus.com).

	Socio-ecological system	**Tipping point**
Synonyms	Social-ecological system	Abrupt change
	Bioeconomic model	Threshold
	Socio-ecological system	Regime shift
	Socioeconomic-ecological system	Regime change
	CHANS	
	Coupled human and natural system	

of tipping points. A key aspect was whether the results of a study gave recommendations or formed the basis for management.

2.4 Results

2.4.1 Variability in Terminology Between Marine Case Studies

Publication dates of the 38 studies range from 1990 to 2017 with the majority of studies published after 2010. We distinguished between case studies (63%), reviews (21%) and theoretical studies (16%) (Fig. 2.2). Within these publications the use of the term 'SES' is most prevalent. Other terms include 'bioeconomic model' or 'human-environment system' (Renaud et al., 2010). 74 % of the studies provided no further definition of the concept of SES, while definitions varied greatly among the remaining publications. Hansen (2014) defined SES as a "complex adaptive system in which people rely on ecosystem services and are key drivers of ecosystems", whereas Renaud et al. (2010), adopting the definition by Gallopin (1991), stated that "an SES is defined as a system that includes societal (human) and ecological (biophysical) subsystems in mutual interaction". Compared to SES, we observed an even greater variation in the terminology used for TPs. Frequently multiple terms are used synonymously in the same article (Fig. 2.2).

The most frequently used term for TP was 'threshold' (45%), followed by 'regime shift' (42%). The actual word 'tipping point' was only used in 21% of the cases. Additionally, terms such as 'transition' (Joseph et al., 2013) or 'transformation' (Andrachuk and Armitage, 2015) were used as synonyms (Fig. 2.3b). Similar to terminology, definitions of TPs varied between the studies; TPs were not defined in 39% of the cases. A few

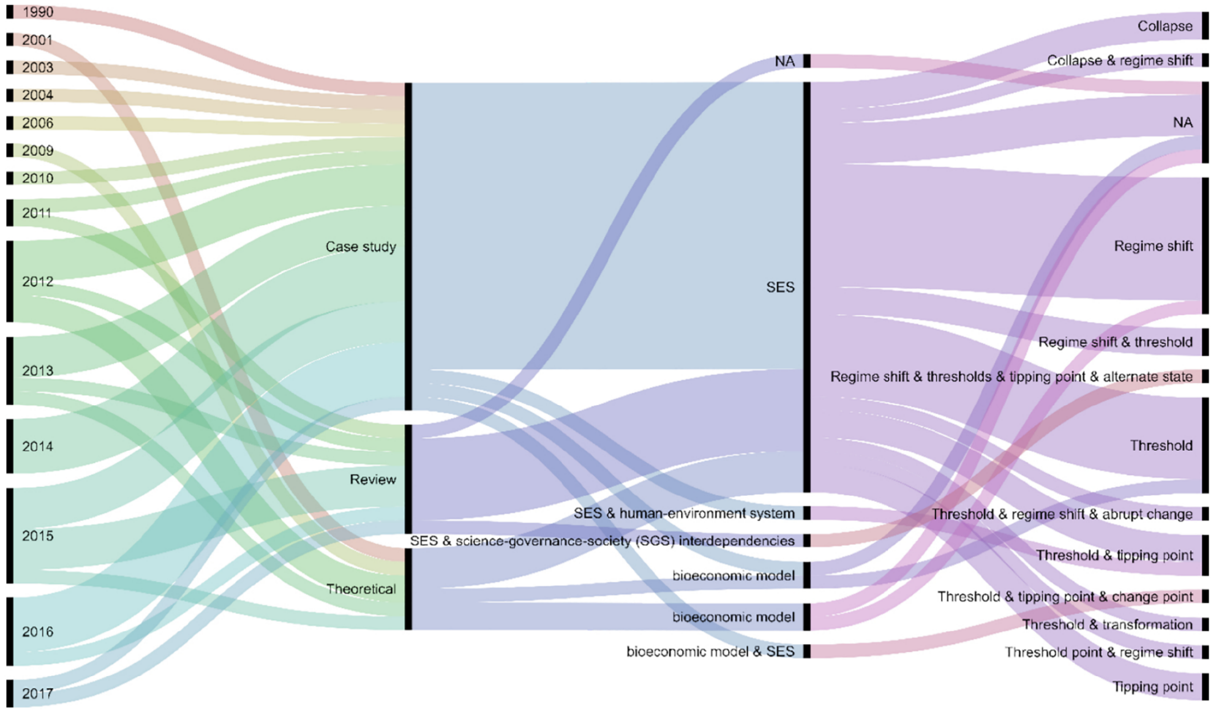


Figure 2.2: Alluvial diagram of publication dates, article type and terminology used for socio-ecologycal system (SES) and tipping point (TP) of 38 articles retained after screening using RAWGraphs Visualisation Platform (Mauri et al., 2017). The height of the back bars (nodes) and coloured lines is proportionally to the flow quantity and shows the number of publications represented.

studies gave very brief definitions such as 'a fundamental shift in system characteristics that result in a qualitatvely different system identity' (Andrachuk and Armitage, 2015) or "ecosystems rapidly change to a contrasting state" (Nyström et al., 2012), while other cases presented a very detailed description of criteria that must be met to define a TP (e.g. Cumming and Peterson (2017)). We also observed that the definition of TP depends on the sub-system in which it occurred (economic, ecological, social or a combination of those) (Fig. 2.3d).

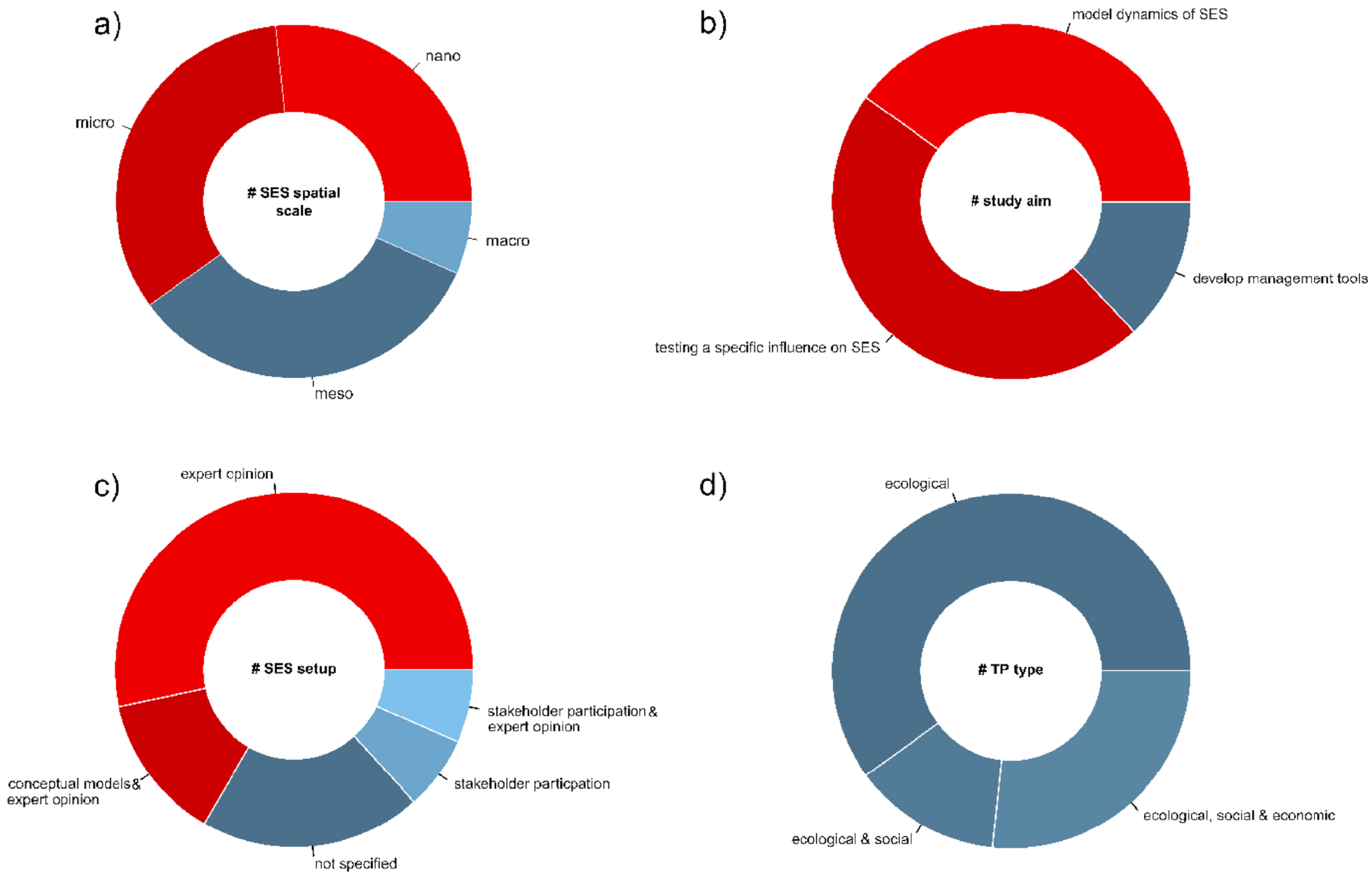


Figure 2.3: Percentage share of a) spatial scale to which the study relates, b) objectives the study are aiming for, c) different approaches that define which SES components to include in an empirical assessment and their frequency of application and d) sub-system of the SES in which the described TP occurs in the 15 empirical case studies describing tipping points (TP) in socio-ecological system (SES).

2.4.2 SES Complexity and Diversity of Assessment Approaches

One aim of this study was to identify whether TPs and SES are being used to inform management (e.g. management to avoid cascading effects in SES), hence we selected only empirical case studies for further analysis. In total, only 15 of the 38 studies qualify as empirical studies (for details see supplementary material Fig. 2.5). In terms of the geographical scale we found that practical SES and TP research is predominately applied on a small geographical scale (e.g. "The German Bight of the North Sea"; Burkhard and Gee, 2012), in most cases describing the state, regulation and use of a single biological resource (Fig. 2.3a). All but three case studies focused on a single fisheries resource and the connectivity and interdependencies of the corresponding SES (Fig. 2.4). The temporal aspect is addressed by 14 out of 15 (93%) studies.

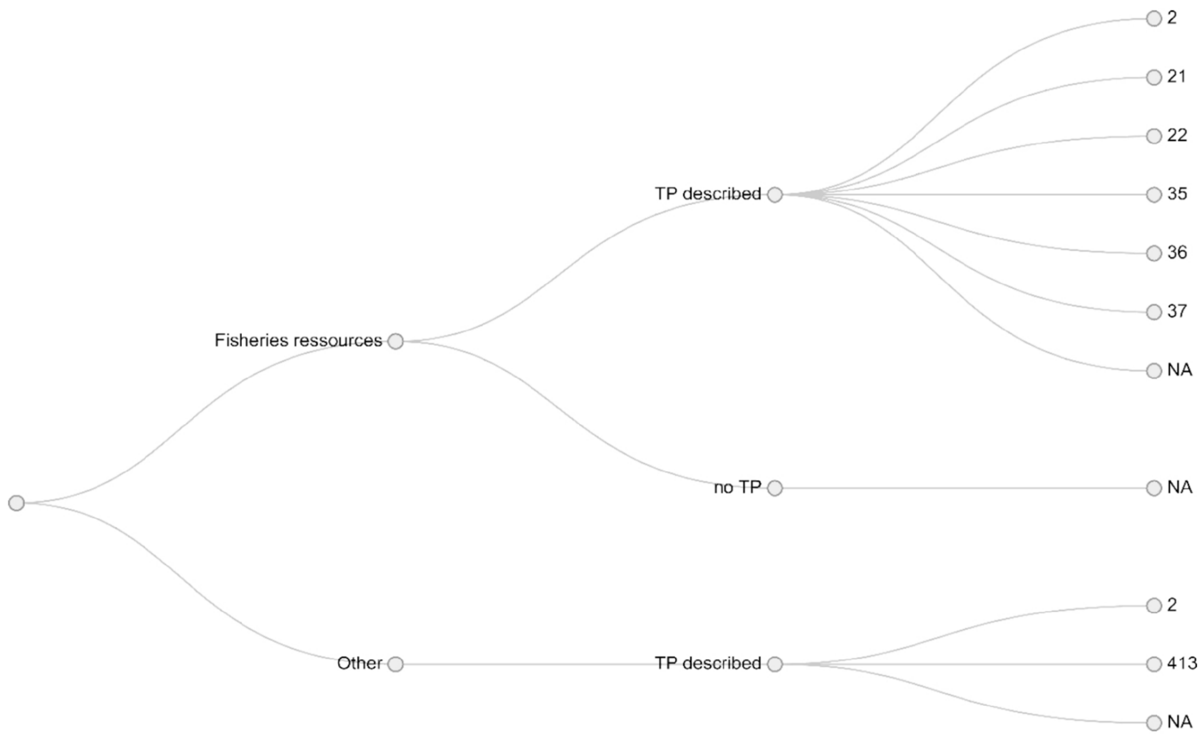


Figure 2.4: Cluster dendrogram representing the spread of case studies addressing fisheries resources (80% out of 15 case studies), describing tipping points and the related number of SES components included (RAWGraphs Visualisation Platform ; Mauri et al. (2017)).

The aims of the case studies analysed can be summarised as descriptions of an SES by applying different modelling approaches (40%), testing for the influence of specific agents on the respective SES (47%), and concrete problem phrasing and development of management tools for a practical issue (13%) (Fig. 2.3b). Examples of the latter are Perry and Masson (2013) who established an index of large scale changes in the Strait of Georgia and Canada, and McClanahan et al. (2011) who developed critical reference points for the sustainable management of coral reefs of the western Indian Ocean.

Scientific approaches to SES set-up (Fig. 2.3c) and assessment approaches (Table 2.2) vary widely among the studies. In most cases expert opinions, sometimes in combination with conceptual models, are used to identifiy SES components for subsequent analyses. Surprisingly, we only found three cases where stakeholders were involved to conceptualise the SES (Fig. 2.3c). The number of SES components and therefore the level of complexity varied considerably between studies, ranging from two (McClanahan et al., 2011; Renaud et al., 2010) to 413 in a modelling study which simulated all SES status indicators and processes (Banos-González et al., 2016). Although the studies qualified as empirical, in six cases no further specification of the number of SES components was given. Five studies aggregated 20 to 40 SES components for their respective analyses and all but one study were based on empricical data (Fig. 2.4).

Table 2.2: Eight different methods used to analyse spatio-temporal aspects of SES and their application in key studies. In total, 8 studies focused on temporal (t) assessments, while 6 studies considered spatio-temporal (st) aspects.

Study	Spatio-temporal aspects considered	**Generalised socio-ecological model**	**Ecological model (growth, population, etc)**	**Ecosystem services indicators**	**DPSIR /conceptual framework**	**Mulitvariate statistics**	**Descriptive**	**Decision support tool (e.g VENSIM simulation software)**	**Stakeholder consulation**
Lade and Niiranen (2017)	t	1							
Lade et al. (2015)	t	1							
McClanahan et al. (2011)	t		1						
Burkhard and Gee (2012)	st		1	1					
Dearing et al. (2015)	t			1					
Perry and Masson (2013)	t				1	1			
Broderstad and Eythórsson (2014)	t						1		
Banos-González et al. (2016)	t							1	
Serrao-Neumann et al. (2016)	st				1				
Conrad and Rondeau (2015)	st		1						
Andrachuk and Armitage (2015)	t								1
Eriksson et al. (2015)									1
Renaud et al. (2010)	st						1		
Hansen (2014)	st						1		
Joseph et al. (2013)	st								1
Sum		**2**	**3**	**2**	**2**	**1**	**3**	**1**	**3**

2.4.3 Cascading Effects in Marine SES

The majority of the empirical studies reviewed (60%) located the TP solely in the ecological sub-system, four studies (27%) in all three sub-systems. One exception described two simultaneous TPs in the ecological and the social sub system (Burkhard and Gee, 2012). The number of TPs identified ranged from one in 33% of the case studies to seven in one case study (Broderstad and Eythórsson, 2014). The majority studies described one or multiple TPs in the ecological resource of the SES (Fig. 2.3d). Others put emphasis on physical changes that affect the SES (Dearing et al., 2015), or a TP in the relationship between the amount of ecological resource and other parameters within the SES (Perry and Masson, 2013).

With regard to cascading or knock-on effects, just about half of the studies (47%) identified a translation of the effect of the TP from one sub-system to one or more components. Serrao-Neumann et al. (2016) described three respective case studies of TP in SES. In all three cases TPs were crossed in the ecological as well as the social and economic spheres. In one case anthropogenic impacts in combination with natural pressures induced TP(s) in the SES: a change in the coral species composition and a loss of seagrass was caused by decreasing water quality due to increasing nutrients and turbidity by land run-off in combination with flood events. Most likely substantial development in the region led to increasing anthropogenic pressures (increased nutrient loads and suspended solids leading to deteriorating water quality). The authors described cascading effect to the socio-cultural sub-system which resulted in a decline in tourism, amenity and fishing. The two other case studies described natural pressure induced TPs in the ecological sphere cascading into the socio-cultural and economic sub-systems. Hence, climatic events caused an undesired increase or decrease in a species which altered the ecosystem in an unwanted way leading to a decline or loss in the fished resource. This in turn led to fisheries demise, tourism decline and loss of livelihoods. Perry and Masson (2013) identified a combination of natural (indicated by temperature, wind speed and the North Pacific Gyre Oscillation index) and human (reflected by human population number, fishing effort and fry release number) pressures inducing TP in the SES. Likewise, Dearing et al. (2015) found that human pressures in combination with climate caused TP. Here, authors described an interesting feedback mechanism where the degrees of human modification strongly interacts with the resilience of natural ecosystems to climate change.

Regarding cascading or knock-on effects, about the other half of the studies (53%) did not describe an effect of the TPs on other SES components or spheres, although a change in the ecological resource presumably has an impact on the other sub-systems of an SES (Ostrom, 2007). One study described the impact of one external shock on all three spheres of an SES in parallel, but cascading effects of a TP in the ecological system on the social sub-system have been avoided by feedback mechanisms (Renaud et al., 2010). A cascading effect through all three subsystems (ecological, economic and social) was only described by Joseph et al. (2013). In this case study the cascade moved down from ecological change resulting in destruction of resources, leading to economic impacts and affected livelihood which then resulted in occupational change in the related communities. We found that this description of a feedback loop within the socio-cultural sphere of the SES is rarely described across the reviewed studies. Most papers focused on the ecological changes and feedback loops, describing e.g. predator-to-prey loops (Lade and Niiranen, 2017) or feedbacks within the food web (McClanahan et al., 2011) or the economic linkages (Conrad and Rondeau, 2015).

2.4.4 SES Vulnerability and Advice for Management

A further aspect of our review was to evaluate whether and how vulnerability and resilience of SES were defined and addressed and whether findings have been used to advise management processes (see assessment criteria Table 2.5). The majority (¿70%) of studies neither addressed the topics of vulnerability or resilience nor gave practical advice for EBM. About 20% of the studies acknowledged the resilience of the respective SES or discussed associated implications but did not analyse it quantitatively or qualitatively. Likewise, only 13% of the papers recognised SES vulnerability. Resilience and vulnerability of the SES were qualitatively analysed by 26% and 20% of the studies, respectively.

Only one study conducted a mixture of quantitative and qualitative assessments of ecosystem resilience by combining ecological modelling with a more qualitative approach concerning the socio-economic system components (Burkhard and Gee, 2012) (see also Table 2.2). A further study described a detailed quantitative vulnerability assessment by applying a sustainability model of the entire SES that allowed analysis of the impact of different climate change scenarios in combination with the effects of certain policy measures (Banos-González et al., 2016).

Although about half of the reviewed studies (53%) addressed management questions for the respective SES, most of the advice was very generic and lacked concrete recommendations for management actions. Broderstad and Eythórsson (2014), for instance, recommended stronger political support for local communities, and Serrao-Neumann et al. (2016) advised greater inter-agency collaboration.

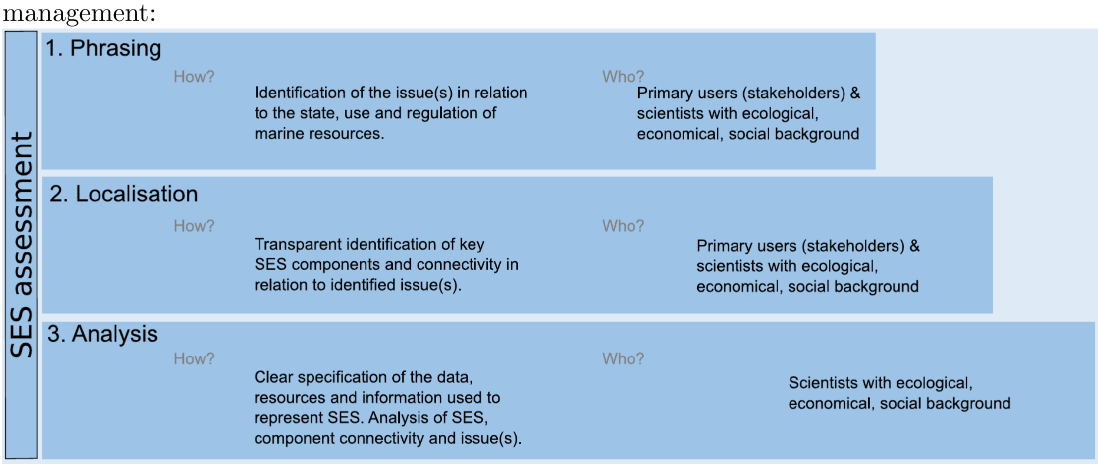
2.4.5 Guiding Principles for the Operationalisation of SES Frameworks

One main conclusion from our review is that studies need to become more transparent in how they are defining SES and what exactly they are analysing. A more focused approach would strengthen the analytical use of the SES and TP concepts, not least by making studies more easily comparable. The use of decision support tools such as the VENSIM software (Ventana System, 2011), classically used for the analysis of management systems, are promising approaches to master the high level of complexity inherent to SES and to come to a better understanding of marine SES.

In order to facilitate the uptake of SES and TP-related concepts in marine resource or spatial management, we propose practical guidelines to aid defining explicit links between SES, TPs and management decisions with special emphasis on who needs to participate in that process (Box 2.2). Our 3-step procedure includes phrasing (1), localisation (2) and analysis (3). In the first step (phrasing) the issue, which can be e.g. a TP in the ecological system, an undesired economic sub-system state or a societal demand, has to be identified. This issue has to be put into relation of the SES state and the use and regulation of the marine resource. For the second step (localisation) a transparent identification of SES components, components' connectivity and feedback mechanisms needs to be operated in relation to the in step (1) identified issue. In the third step (analysis) a precise and clear specification of the data available, the resources and information that is used to represent the SES is required to perform an analysis of the SES, the component connectivity and the defined issue. Although it has been stated by Walker et al. (2010) that stakeholders should be included in the process of resilience assessments, our findings show that already at the level of defining an SES, stakeholders are more or less not consulted (Fig. 2.3c). Additionally, it still seems unclear who should participate when it comes to the operationalisation of SES frameworks (Table 2.2; Fig. 2.3c). We suggest that in the first (phrasing) and second (localisation) step of our guideline stakeholders knowledge, that only primary users in first line have, should be part of the process. In the present review, we found that with the sub-system considered, definitions and terminology of SES and TP is varying. Likewise, it can be assumed that scientific focus will vary with the background of the researcher. Thus, we propose an interdisciplinary research approach that requires in all three steps the involvement of scientists from the fields of ecology, economy and social sciences. Otherwise aspects from single fields might be underrepresented or overseen.

Infobox 2.2 Guiding principles for the operationalisation of SES frameworks

To address the shortcomings identified here in marine applications of SES frameworks, we propose a simple 3-step procedure for empirically analysing SES in the context of marine resource management:



The first step is problem phrasing, in which the issues in relation to marine resources and the boundaries of the SES in question are defined by stakeholders in particular primary users and a multidisciplinary team of scientists. In the second step of problem localisation potential TPs and the key SES components are defined together with the degree of connectivity between these components. Consideration is also needed of spatio-temporal aspects at this stage, requiring a collaborative effort of stakeholders and scientists. In the last step of problem analysis the vulnerability of the SES to the occurrence of TPs is established, differentiating between pressures leading to a TP which can readily be regulated through the implementation of management measures and those that require a different approach. Analysis should firstly aim to identify the root causes of a TP, so that management can be designed to prevent it from being reached. For this purpose, it is important to understand in which spheres and components of the SES tipping points are located, how resilient and vulnerable these components are to which agents of change and what measures could mitigate the potential risks of their tipping.

2.5 Discussion

Our results show that empirical application of the concept of socio ecological systems (SES) and their vulnerability to tipping points (TPs) in the marine realm is still in its infancy. There is a striking lack of harmonised terminology and stakeholder engagement, and a high diversity in assessment approaches. Many studies focus on small geographical scales, mostly addressing consequences of changes in fisheries resources. All empirical studies addressing TPs in SES show a distinct lack of transparency with regard to the data resources used and assumptions made. Furthermore, the majority of the reviewed studies on marine SES are only conceptual in nature, describing frameworks of SES, assuming how an SES or a selected group of components might behave or considering how an SES could be quantitatively modelled.

In more detail, locations of TPs within the SES, most studies reviewed here describe the 'tipping' of an ecological resource or a component within the ecological sub-system and knock-on effects resulting from that TP. Generally, the analysis of TPs and resulting cascading effects within SES is not trivial as the detection of both depends largely on the SES setup (Steffen et al., 2018). A prerequesite for the identification of a TP and subsequent knock-on effects is detailed knowledge about the connections and interlinkages between the sub-systems within the SES. In the context of EBM, the consequences of a TP are of concern from a policy perspective. In contrast to governance processes involved in setting goals and priorities, the aim of a management processes is to identify, in consultation with stakeholders, the root causes of a TP to avoid the consequences and the repercussions that it could have on policy (Cormier et al., 2017). However, the consequences of having reached an ecosystem TP can also result in a cascade of TPs across, economic and social (including legal and political) systems (Cooper, 2013; Cormier et al., 2013; Elliott et al., 2017). In an SES context, assessment of TPs would have to integrate the causal pathways of the consequences across the SES to inform managers and stakeholders as to the socio-cultural and economic or even the legal and political consequences. Importantly, these would likely need different mitigation strategies than the management measures needed to prevent the root causes of the TP (Serrao-Neumann et al., 2016). Such an approach requires transdisciplinary research to operationalise SES considerations in management in addition to current monitoring approaches (Leenhardt et al., 2015).

Our results show that the social sphere of the SES investigated is often underrepresented and does not feature as a starting point for investigation. In the reviewed cases, the researchers tended to focus on the biological resource in their analyses, while inter- or transdisciplinary approaches that incorporate social sciences are still rather rare (Leslie et al., 2015).

This may partially be caused by the fact that we cannot claim the review to be comprehensive, and that potential synonyms for TP or SES may have been missed in the initial Scopus key word search (e.g. critical transition, transformation or coupled human–environment systems). However, the homogeneous picture observed is most likely resulting from the general conceptualisation of the SES without the involvement of stakeholders, in addition to the composition of the team of researchers. In most of the cases we found that the authors' opinion was the foundation for setting up an SES. In other words, the decision as to which components to include in the SES was solely that of the researcher or team of researchers. This subjective perception can be problematic and may lead to certain (preventable) risks when assessing an SES. As we have shown, the scientific background of the authors determines the definition, terms and use of the concepts of TP and SES, which is likely to colour the setup and also the outcomes of any subsequent assessment. We contend that the intrinsic nature of an SES requires both transdisciplinary approaches and a high degree of interdisciplinarity. Social elements were neglected across the board, meaning the understanding of the SES in question is likely to be incomplete. We postulate that a participatory approach, including many stakeholders with different societal backgrounds will substantially reduce the risk of ending up with a biased view of the SES or missing important aspects of the system. This is all the more important when addressing human needs in relation to the use of marine resources. Only three rewiewed studies are based on stakeholder participation. Social, ethical and political values may be missed when stakeholder knowledge is ignored and only scientific perception is included (Middendorf and Busch, 1997); incorporation of a variety of perspectives will also result in a more representative rationale and reduction of uncertainties (Olsson et al., 2004). Despite evidence that competing interests of stakeholders can make participation processes difficult, especially for adaptive management approaches (Brody, 2003), incorporation of insights from stakeholders when defining an SES and its constituent processes is therefore crucial as a starting point for management (Walker et al., 2002; Stringer et al., 2006;

Leslie et al., 2015). Thus, if the dynamics and specifically SES vulnerability to tipping points are to be investigated, a clear link between problem definition and key stakeholders should be established (see Box 2.2).

2.6 Conclusion

Societal and consequently the scientific interest in the influence of TPs on SES has grown exponentially over the last two decades. A variety of terminologies, definitions and concepts have emerged as a result, leading to a certain opacity. Practical operationalisation of these concepts has so far remained difficult, especially in the marine environment where SES and TP-related studies are still scarce (Walker and Meyers (2004); Carpenter and Brock (2006); this review). One reason may be the added complexity of marine SES in that they transcend land-sea boundaries. Thus the ecological sub-system (related to the resource use or provision of ecosystem service) is often geographically distant from the social-economic sub-systems that make use of the resource, and it can be difficult to delineate the boundaries and interconnections in these systems, especially where the marine environment is still not fully understood. As yet empirical research is mainly limited to small scale case studies, which is probably due to the high level of complexity of SES. This calls for new approaches that reduce the complexity of SES and prioritise connectivity within an SES, which would enable the concept to be applied in larger and likely more complex settings such as coastal-marine systems. With the principles presented here the link between SES research and management processes can be strengthened through comprehensive participative approaches that involve stakeholders from the start. This calls for transdisciplinary research approaches which should be promoted in future SES research.

2.A Annex

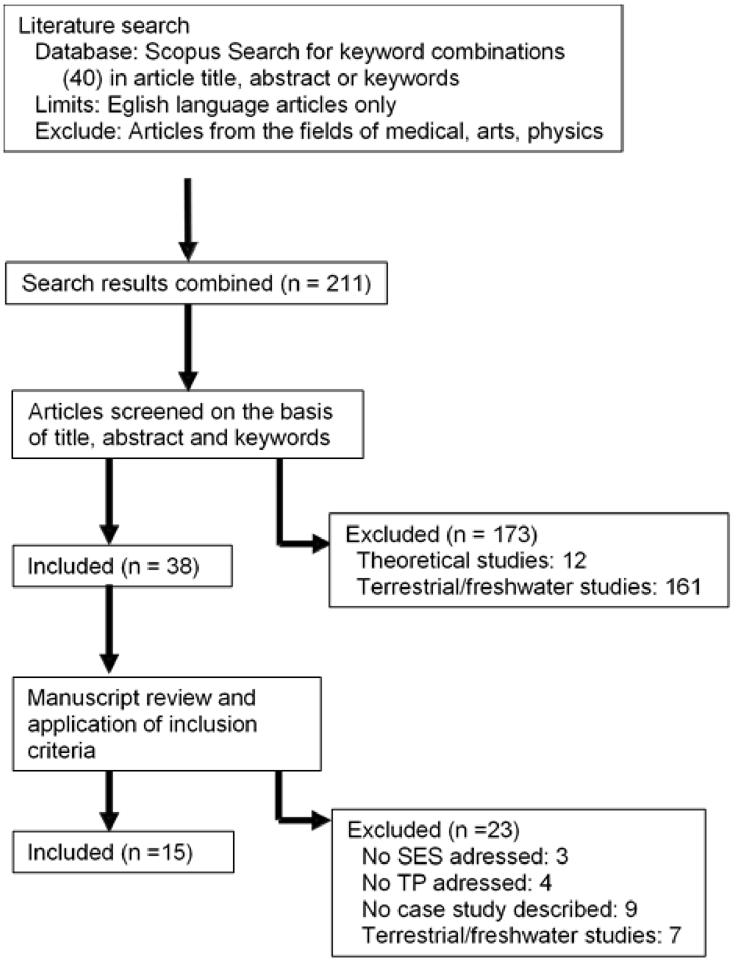


Figure 2.5: Flow chart describing the systematic literature search. Illustrated are the results of the initial search and the selection process of screening and final full text review.

Table 2.3: Search String for the systematic review of scientific articles executed in Scopus on 16th Oktober 2017

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TITLE-ABS-KEY ( "social-ecological" AND "abrupt change" ) OR
TITLE-ABS-KEY ( "CHANS" AND " abrupt change " ) OR
TITLE-ABS-KEY ( "socio-ecological" AND " abrupt change " ) OR
TITLE-ABS-KEY ( "social-ecological system" AND " abrupt change " ) OR
TITLE-ABS-KEY ( "bioeconomic model" AND " abrupt change " ) OR
TITLE-ABS-KEY ( "coupled human and natural system" AND " abrupt change " ) OR
TITLE-ABS-KEY ( "socio-ecological system" AND " abrupt change " ) OR
TITLE-ABS-KEY ( "socioeconomic-ecological system" AND " abrupt change " ) OR
TITLE-ABS-KEY ( "social-ecological" AND "threshold" ) OR
TITLE-ABS-KEY ( "CHANS" AND " threshold" ) OR
TITLE-ABS-KEY ( "socio-ecological" AND "threshold" ) OR
TITLE-ABS-KEY ( "social-ecological system" AND "threshold" ) OR
TITLE-ABS-KEY ( "bioeconomic model" AND "threshold" ) OR
TITLE-ABS-KEY ( "coupled human and natural system" AND "threshold" ) OR
TITLE-ABS-KEY ( "socio-ecological system" AND "threshold" ) OR
TITLE-ABS-KEY ( "socioeconomic-ecological system" AND "threshold" ) OR
TITLE-ABS-KEY ( "social-ecological" AND "tipping point" ) OR
TITLE-ABS-KEY ( "CHANS" AND "tipping point" ) OR
TITLE-ABS-KEY ( "socio-ecological" AND "tipping point" ) OR
TITLE-ABS-KEY ( "social-ecological system" AND "tipping point" ) OR
TITLE-ABS-KEY ( "bioeconomic model" AND "tipping point" ) OR
TITLE-ABS-KEY ( "coupled human and natural system" AND "tipping point" ) OR
TITLE-ABS-KEY ( "socio-ecological system" AND " tipping point" ) OR
TITLE-ABS-KEY ( "socioeconomic-ecological system" AND " tipping point" ) OR
TITLE-ABS-KEY ( "social-ecological" AND "regime shift" ) OR
TITLE-ABS-KEY ( "CHANS" AND " regime shift" ) OR
TITLE-ABS-KEY ( "socio-ecological" AND " regime shift" ) OR
TITLE-ABS-KEY ( "social-ecological system" AND " regime shift" ) OR
TITLE-ABS-KEY ( "bioeconomic model" AND " regime shift" ) OR
TITLE-ABS-KEY ( "coupled human and natural system" AND " regime shift" ) OR
TITLE-ABS-KEY ("socio-ecological system" AND "regime shift" ) OR
TITLE-ABS-KEY ( "socioeconomic-ecological system" AND " regime shift" ) OR
TITLE-ABS-KEY ( "social-ecological" AND "regime change" ) OR
TITLE-ABS-KEY ( "CHANS" AND " regime change" ) OR
TITLE-ABS-KEY ( "socio-ecological" AND " regime change" ) OR
TITLE-ABS-KEY ( "social-ecological system" AND " regime change " ) OR
TITLE-ABS-KEY ( "bioeconomic model" AND " regime change " ) OR
TITLE-ABS-KEY ( "coupled human and natural system" AND " regime change " ) OR
TITLE-ABS-KEY ( "socio-ecological system" AND "regime change " ) OR
TITLE-ABS-KEY ( "socioeconomic-ecological system" AND " regime change" ) AND
( EXCLUDE ( DOCTYPE , "ch " ) OR EXCLUDE ( DOCTYPE , " bk " ) ) AND ( EXCLUDE (
SUBJAREA , "MEDI " ) OR EXCLUDE ( SUBJAREA , " ARTS " ) OR EXCLUDE ( SUBJAREA , "
COMP " ) OR EXCLUDE ( SUBJAREA , " PHYS " ) OR EXCLUDE ( SUBJAREA , " CENG " ) OR
EXCLUDE ( SUBJAREA , " PHAR " ) OR EXCLUDE ( SUBJAREA , " PSYC " ) OR EXCLUDE (
SUBJAREA , " CHEM " ) OR EXCLUDE ( SUBJAREA , " IMMU " ) OR EXCLUDE ( SUBJAREA , "
NEUR " ) OR EXCLUDE ( SUBJAREA , " VETE " ) ) AND ( LIMIT-TO ( LANGUAGE , "English
" ) )
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Table 2.4: Result of the systematic literature search for empirical marine case studies describing tipping points in socio-ecological systems by study type category.

Article type	**Author**	**Year**	**Title**
case study	Andrachuk, M. and Armitage, D.	2015	Understanding social-ecological change and transformation through community perceptions of system identity
case study	Banos-González, I., Martínez-Fernández, J., Esteve, M.A.	2016	Tools for sustainability assessment in island socio-ecological systems: an application to the Canary Islands
case study	Bosch D.j. and Shabman L.A.	1990	Simulation Modeling to Set Priorities for Research on Oyster Production
case study	Bottom, D.L., Jones, K.K., Simenstad, C.A., Smith, C.L.	2009	Reconnecting social and ecological resilience in salmon ecosystems
case study	Bozzeda, F., Zangrilli, M.P., Defeo, O.	2016	Assessing sandy beach macrofaunal patterns along large-scale environmental gradients: A Fuzzy Naïve Bayes approach
case study	Broderstad, E.G. and Eythórsson, E.	2014	Resilient communities? Collapse and recovery of a social-ecological system in Arctic Norway
case study	Burkhard, B., Gee, K.	2012	Establishing the resilience of a coastal-marine social-ecological system to the installation of offshore wind farms
case study	Butler, J.R.A., Wong, G.Y., Metcalfe, D.J., Honzák, M., Pert, P.L., Rao, N., van Grieken, M.E., Lawson, T., Bruce, C., Kroon, F.J., Brodi,e J.E.	2011	An analysis of trade-offs between multiple ecosystem services and stakeholders linked to land use and water quality management in the Great Barrier Reef, Australia

case study	Cranford, P.J., Kamermans, P., Krause, G., Mazurié, J., Buck, B.H., Dolmer, P., Fraser, D., Van Nieuwenhove, K., O'Beirn, F.X., Sanchez-Mata, A., Thorarinsdóttir, G.G., Strand, Ø.	2012	An ecosystem-based approach and management framework for the integrated evaluation of bivalve aquaculture impacts
case study	Eriksson, H., de la Torre-Castro, M., Purcell, S.W., Olsson, P.	2015	Lessons for resource conservation from two contrasting small-scale fisheries
case study	Gain, A.K. and Giupponi, C.	2014	Impact of the Farakka Dam on thresholds of the hydrologic: Flow regime in the Lower Ganges River Basin (Bangladesh)
case study	Hansen, W.D.	2014	Generizable principles for ecosystem stewardship-based management of social-ecological systems: lessons learned from Alaska
case study	Hossain, Md.S., Dearing, J.A., Rahman, M.M., Salehin, M.	2016	Recent changes in ecosystem services and human well-being in the Bangladesh coastal zone
case study	Joseph, V., Thornton, A., Pearson, S., Paull, D.	2013	Occupational transitions in three coastal villages in Central Java
case study	Kinzig, A.P., Ryan, P., Etienne, M., Allison, H., Elmqvist, T., Walker, B.H.	2006	Resilience and regime shifts: Assessing cascading effects
case study	Kopf et al.	2015	Anthropocene baselines: Assessing change and managing biodiversity in human-dominated aquatic ecosystems
case study	Lade, S.J. and Niiranen, S.	2017	Generalized modeling of empirical social-ecological systems
case study	Lade, S.J., Niiranen, S., Hentati-Sundberg, J., Blenckner, T., Boonstra, W.J., Orach, K., Quaas, M.F., Österblom, H., Schlüter, M.	2015	An empirical model of the Baltic Sea reveals the importance of social dynamics for ecological regime shifts
case study	Neis, B., Gerrard, S., Power, N.	2013	Women and Children First: the Gendered and Generational Social-ecology of Smaller-scale Fisheries in Newfoundland and Labrador and Northern Norway

case study	Perry, R.I. and Masson, D.	2013	An integrated analysis of the marine social-ecological system of the strait of Georgia, Canada, over the past four decades, and development of a regime shift index
case study	Pope, K.L., Allen, C.R., Angeler, D.G.	2014	Fishing for Resilience
case study	Renaud, F.G., Birkmann J., Damm M., Gallopín G.C.	2010	Understanding multiple thresholds of coupled social-ecological systems exposed to natural hazards as external shocks
case study	Renaud F.G., Syvitski, J.P.M., Sebesvari, Z., Werners, S.E., Kremer, H., Kuenzer, C., Ramesh, R., Jeuken, A., Friedrich, J.	2013	Tipping from the Holocene to the Anthropocene: How threatened are major world deltas?
case study	Serrao-Neumann, S., Davidson, J.L., Baldwin, C.L., Dedekorkut-Howes, A., Ellison, J.C., Holbrook, N.J., Howes, M., Jacobson, C., Morgan, E.A.	2016	Marine governance to avoid tipping points:Can we adapt the adaptability envelope?
rewiev	Cumming, G.S. and Peterson, G.D.	2017	Unifying Research on Social–Ecological Resilience and Collapse
rewiev	Dearing, J., Acma, B., Bub, S., Chambers, F., Chen, X., Cooper, J., Crook, D., Dong, X., Dotterweich, M., Edwards, M., Foster, T., Gaillard, M.-J., Galop, D., Gell, P., Gil, A., Jeffers, E., Jones, R., Anupama, K., Langdon, P., Marchant, R., Mazier, F., McLean, C., Nunes, L., Sukumar, R., Suryaprakash, I., Umer, M., Yang, X., Wang, R., Zhang, K.	2015	Social-ecological systems in the Anthropocene: The need for integrating social and biophysical records at regional scales
rewiev	Kelly, R.P., Erickson, A.L., Mease, L.A., Battista, W., Kittinger, J.N., Fujita, R.	2015	Embracing thresholds for better environmental management

rewiev	McClanahan, T.R., Graham, N.A.J., MacNeil, M.A., Muthiga, N.A., Cinner, J.E., Bruggemann, J.H., Wilson, S.K.	2011	Critical thresholds and tangible targets for ecosystem-based management of coral reef fisheries
rewiev	Nyström, M., Norström, A.V., Blenckner, T., de la Torre-Castro, M., Eklöf, J.S., Folke, C., Österblom, H., Steneck, R.S., Thyresson, M., Troell, M.	2012	Confronting Feedbacks of Degraded Marine Ecosystems
rewiev	Österblom, H., Merrie, A., Metian, M., Boonstra, W.J., Blenckner, T., Watson, J.R., Rykaczewski, R.R., Ota, Y., Sarmiento, J.L., Christensen, V., Schlüter, M., Birnbaum, S., Gustafsson, B.G., Humborg, C., Mörth, C.-M., Müller-Karulis, B., Tomczak, M.T., Troell, M., Folke, C.	2013	Modeling social-ecological scenarios in marine systems
rewiev	Thrush, S.F., Lewis, N., Le Heron, R., Fisher, K.T., Lundquist, C.J., Hewitt, J.	2016	Addressing surprise and uncertain futures in marine science, marine governance, and society
rewiev	Walker, B., Meyers, J.	2004	Thresholds in Ecological and Social–Ecological Systems: a Developing Database
theoretical	Barnett, J., Adger, W.N.	2003	Climate Dangers and Atoll countries
theoretical	Bulte, E. and van Kooten, G.	2001	Harvesting and conserving a species when numbers are low: Populatin viability and gambler's ruin in bioeconomic models
theoretical	Carmack, E.C., McLaughlin, F.A., Whiteman, G., Homer-Dixon, T.F.	2012	Detecting and coping with disruptive shocks in Arctic marine systems: A resilience approach to place and people
theoretical	Conrad, J.M. and Rondeau, D.	2015	Bioeconomics of a Marine Disease
theoretical	Ishimura, G., Herrick, S., Sumaila, U.R.	2012	Fishing games under climate variability: Transboundary management of Pacific sardine in the California Current System

theoretical	Lade, S.J., Tavoni, A., Levin, S.A., Schlüter, M.	2013	Regime shifts in a socio-ecological system

Table 2.5: Criteria used to systematically assess the 38 studies selected for the final evaluation.

Asssement criteria	***Description***	***Type of answer***
Article type	Classification of the article to standardised categories	Optional answer: theoretical/review/case study
Terminology of SES	Wording used in the article to describe 'SES'	Open answer
Definition SES	Definition of SES given in the article	Open answer
Terminology of tipping point	Wording used in the article to name 'tipping point'	Open answer
Definition of tipping point	Definition of tipping point given in the article	Open answer; if definition is adopted from another reference, please cite reference
Aim of study	Describe the aim of the study or the research question if applicable	Open answer
Case study	Is there a case study (modelling study) described?	Optional answer: yes/no
Data based case study	Is the case study based on real data?	Optional answer: yes/no
Spatio-temporal considerations	Are there or spatio-temporal aspects considered in the SES?	Optional answer: temporal/ spatial/spatio-temporal
Geolocation	Location and extend of case study	Open answer
Methods	Which methods are used to analyse the system?	Open answer
SES setup	How was the SES defined?	Open answer
N components	How many components does the described SES consist of?	Open answer
Components	Name components	Open answer
Fisheries ressources	Does the study consider fisheries resources?	Optional answers: yes/no
SES framework	Which other factor/s influence the SES & TP?	Open answer
Tipping point described	Is a tipping point described?	Optional answer: yes/no
N Tipping points	How many tipping points?	Open answer
Which tipping point/s	Description of the tipping point/s	Open answer
Type of tipping point	Where did the initial tipping point occur?	Optional answers: ecology/society/economics
Tipping components	How many components are 'tipping'?	Open answer
Method	How are tipping points analysed?	Open answer: Description of method
Management scenarios	Are management scenarios assessed?	Optional answer: yes/no
Cascading effect	Are other components described that did not 'tip' but were affected by the tipping point?	Optional answer: yes/no
Components affected	How many components are affected?	Open answer
Resilience	Is resilience of the SES mentioned, addressed or analysed?	Optional answers: mentioned/addressed/ analysed
Advice for Management	Does the study give advice to resource management?	Optional answer: yes/no
Which advice	Briefly outline the advice given	Open answer

Chapter 3

A Fisheries Social-Ecological System at Risk of Losing Its Capacity to Adapt to Global Change

Abstract: Global change challenges coupled human-nature-systems such as fisheries socio-ecological systems (SESs) because they are confined by spatial and functional ecosystem boundaries, and human livelihoods often depend on their stable environmental, socio-economic and socio-cultural states. Understanding the capacity of an SES to adapt to changing ecological or socio-economic conditions is complex and entails disentangling the system's properties such as resilience, vulnerability and adaptive capacity. Here, we quantified autonomous adaptation strategies of a German demersal fishery SES in the southern North Sea to environmental and socio-economic change at regional and local scales over the last two decades. Deploying the modified Ostrom framework allowed us to analyse spatio-temporal dynamics of SES attributes and their linkages. Our analysis revealed autonomous adaptations of the SES to environmental and socio-economic change, which entailed a shift in target species, fishing strategies, but importantly a distinct decrease in number of actors. We found that the ability of the SES to adapt decreased with time, with the SES being now on the brink of withstanding future environmental and socio-economic change. Key barriers to adaptation for the fisheries SES are related to fishing cultures, economic structures, political setting and increasing spatial use conflicts. We now find the SES is locked in an undesirable state reflecting a social-ecological trap where social and ecological feedbacks negatively reinforce one another. Our findings highlight the need for tailored and context specific co-management approaches for all decision-making processes to which the SES is exposed to. In-depth understanding of SES components and the linkages of SES attributes is a prerequisite to develop future management approaches to enhance SES adaptive capacity to global change.

Keywords: adaptive capacity, fishing métiers, marine spatial planning, network analysis, stakeholder interviews, North Sea, tipping point

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This chapter is consists of the paper "Fostering the capacity of a fisheries social-ecological system to adapt to global change" in submission to Global Environmental Change by Stelzenmüller, Letschert, Blanz, Blöcker, Claudet, Cormier, Gee, Held, Kannen, Kruse, Rambo, Scharper, Sguotti, Quiroga, and Möllmann (2023).

3.1 Introduction

Global change fuels the social demand to strengthen the adaptive capacity of social-ecological systems (SESs) to resist everchanging ecological or socio-economic conditions. While SES definitions vary, there is consensus about SES components comprising the entities of common pool resources, resource users, and institutions (Colding and Barthel, 2019). In general, SESs can be characterised by the integration of biogeophysical and socio-cultural processes, their complexity and levels of self-organisation, as well as nonlinear and unpredictable dynamics with feedbacks between environmental, as well as socio-economic and socio-cultural processes (Colding and Barthel, 2019; Leenhardt et al., 2015).

Human-ocean interactions are particularly complex and emerging global threats such as climate change are challenging especially for fisheries SES (Visbeck, 2018). Fisheries SESs are confined by spatial or functional ecosystem boundaries and human well-being and livelihoods depend on the exploitation of marine resources and therefore the prevailing environmental, socio-economic and socio-cultural conditions (Partelow, 2018; Perry et al., 2011). In marine ecosystems, climate induced changes of environmental conditions comprise alterations of system productivity and food web dynamics, decline of habitat-forming species, shifts in species distributions, and greater occurrences of diseases (Boyce et al., 2022; Hoegh-Guldberg and Bruno, 2010). Shelf and coastal waters are especially exposed to socio-economical change due to the intensification of the blue offshore economy (Gourvenec et al., 2022) leading to an increase of environmental risks (Bugnot et al., 2020; Turschwell et al., 2022), uncertain cumulative impacts on various ecosystem components (Halpern et al., 2015), and steering the concern of socio-economic impacts on fisheries (Stelzenmüller et al., 2022). In Europe, fisheries SESs are governed by the EU Common Fisheries Policy (CFP; EU Regulation 1380/2013 and EU Regulation 2019/1241), but they are also exposed to local area-based management measures implemented for instance by EU environmental policies (Probst et al., 2021) or the EU Marine Spatial Planning Directive (MSPD; EU Directive 2014/89/EU) (Stelzenmüller et al., 2021). While fisheries governance systems have accepted the complexity of fisheries SES (Hare, 2020), the challenge remains on how to embed SESs and their potential vulnerabilities in decision-making processes in a wider ecosystem approach to management (Lauerburg et al., 2019). Hence, a prerequisite for such decision- making processes is a profound knowledge on the abilities of fisheries SESs to adapt to ecological and social state changes (Salgueiro-Otero and Ojea, 2020).

Understanding the capacity of an SES to adapt to changing ecological or socio-economic conditions is complex and entails a clear differentiation between the system's properties such as resilience, vulnerability and adaptive capacity. SES resilience is often defined as an intrinsic system property with the understanding that a resilient system can respond to uncertainties and adapt toward transformative change (Refulio-Coronado et al., 2021). The vulnerability of a SES is often defined as a function of exposure to disturbance, sensitivity ("sensitivity of the SES to a particular disturbance"), and adaptive capacity ("ability to adapt/withstand to a particular disturbance") (Parry and Intergovernmental Panel on Climate Change, 2007). This concept has been adopted to assess for instance the vulnerabilities of fisheries SES to specific stressors (Johnson et al., 2016; Payne et al., 2021; Thiault et al., 2020, 2018). Adaptive capacity is defined as the SES characteristic that determines whether and to which degree an SES can adjust. Hereafter, adaptive capacity is related to the well-being of the social and ecological elements rather than avoiding large changes (Refulio-Coronado et al., 2021).

SES adaptation can be proactive or reactive (also referred to as autonomous (Pecl et al., 2019), spontaneous or planned (Cottrell et al., 2020), and can be strengthened through adaptive management entailing elements of monitoring, reporting, and refining (Cinner et al., 2019). In the past, fisheries SESs have shown short term or rapid adaptations to changing environmental or socio-economic conditions through, e.g., intensification and diversification of fishing, migration and 'riding out the storm' as well as long-term changes through respective adaptations in policy and governance (Kluger et al., 2020; Perry et al., 2011). Thus, their adaptation strategies can span across ecological (MPA designations, reduction of stressors, etc.), socio-economic (investments, catch diversification of livelihoods, etc.) or institutional (adaptation programmes, coordination and organisation, etc.) realms (Woods et al., 2022).

Here we unravel and quantify autonomous adaptation strategies of the German mixed demersal fishery in the southern North Sea SES to environmental and socio-economic change at regional and local scales over the last two decades. The German plaice related fishery, mainly targeting beside plaice (Pleuronectes platessa) also sole (Solea solea) (Letschert et al., accepted), is a minor actor in the wider North Sea fishery; but an important local resource (Letschert et al., 2021). We here considered all German plaice related fisheries in the southern North Sea as being part of our target SES (Letschert et al., 2021) which operates in an area prone to climate change (Engelhard et al., 2014; Fock et al., 2014; Frelat et al., 2017; Murgier et al., 2021; Sguotti et al., 2022). Furthermore, the SES is being confronted with a rapid spatial expansion of offshore renewables (Stelzenmüller et al., 2022) and marine conservation measures (Probst et al., 2021), forcing many fishing vessels to relocate their effort or adapt the fishing practices in the future (Stelzenmüller et al., 2021).

The general use of models in SES research is compromised both by the degree of realism and the degree of knowledge integration (Schlüter et al., 2012). We identified SES components with the help of the modified Ostrom framework for institutional analysis and development (McGinnis and Ostrom, 2014). We analysed the spatio-temporal dynamics of SES attributes using quantitative statistics and semi-structed interviews to finally untie past adaptive capacities to environmental and socio-economic change. Eventually we conclude on barriers to future SES adaptation within this multi-level governance system and identify future management needs to strengthen adaptive capacities of fisheries SES at risk due to global change.

3.2 Methods

3.2.1 Socio-Ecological System Context and Assessment Framework

Following the rationale described in Lauerburg et al. (2019) we identified the German plaice related fisheries in the southern North Sea as our resource system of interest. We conducted a stakeholder workshop to scope for key SES components, key resources, as well as perceived tipping points that have affected resource exploitation in the past or might do so in the future. The workshop was held on 5th of October 2017 with 21 attendees comprising representatives of the fishing sector (n=6), marine conservation (n=1), academia (n=10), as well as offshore renewable representatives (n=1), and authorities responsible for MSP in the German Exclusive Economic Zone (EEZ) (EU Maritime Spatial planning Directive; (EU Regulation 2014/89/EU) and implementation of EU environmental policies (e.g. Marine Strategy Framework Directive; EU Directive 2008/56/EC) (n=3). Stakeholders identified the rapid expansion of offshore renewables in the southern North Sea, the implementation of fisheries management measures in Natura2000 networks (Mazaris et al., 2019), and climate change as the main drivers of future socio- economic and ecological change. Importantly, stakeholders representing the fisheries sector identified the shift from an Atlantic cod (Gadus morhua) dominated to a flatfish dominated fishery in the early 2000s as an ecological tipping point which had knock-on effects on the actors and the resource system as a whole. The loss of cod as a major resource has forced the fisheries to focus more on a plaice related fishery, itself an adaptation to change.

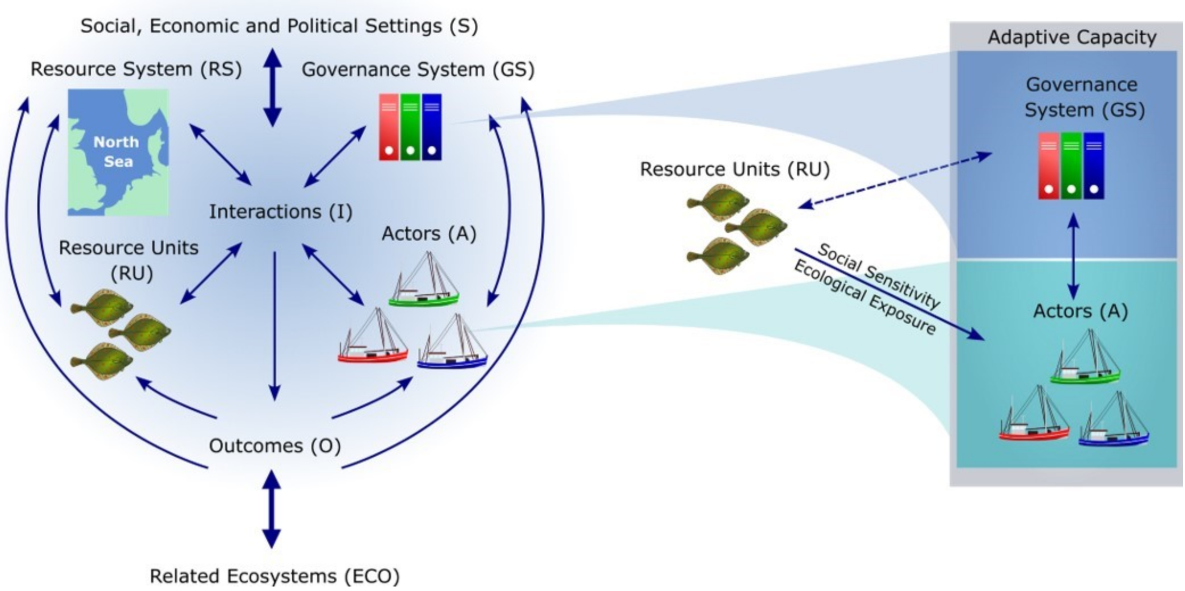


Figure 3.1: Conceptual representation of the social-ecological system structure and illustration of the focus on analysing adaptive capacities related to actors and governance systems (modified from McGinnis and Ostrom (2014)). Resource system (RS) refers to the mixed demersal fisheries in the southern North Sea; Resource units (RU) refers to European plaice; Actors refer to fleets targeting the RU; Governance system (GS) refers to set of institutional arrangements (such as rules, policies, and governance activities) that are used by one or more actors to interact with and govern the RU (see also Table 3.1).

We assessed the adaptive capacity of the SES with the help of the modified Ostrom framework for institutional analysis and development (McGinnis and Ostrom, 2014). This diagnostic tool has been applied in fisheries, forestry, agriculture or watershed management (McGinnis and Ostrom, 2014; Partelow, 2018) and helps to identify SES components comprising resources, actors, governance systems and their linkages and causalities (Colding and Barthel, 2019; Schlüter et al., 2012). We explored the spatio-temporal dynamics of the SES attributes during the past two decades, after the occurrence of the ecological tipping point identified by the stakeholders. Adopting the definitions of previous work (Ban et al., 2017; Cox, 2014), we assumed that the capacity of an SES to adapt depends on actor responses to environmental change and their interaction with the governance system (Figure 3.1). Table 3.1 details the tier 1 and 2 variables of the Ostrom framework with the associated indicators comprising the elements of resource system, resource unit, actors, and governance system. In the following sections we describe the analyses of the respective SES components and attributes in more detail.

3.2.2 Spatio-Temporal Trends of SES Components and Attributes

Resource System and Unit

We characterised climate-related environmental changes at the scale of the entire North Sea and the German EEZ and coastal waters by analysing trends in annual average sea surface temperatures (SST). We focus also on the EEZ and coastal waters since this scale refers to the boundaries of the governance systems described below (see Table 3.1). We used SST data from hindcast runs derived from a coupled atmosphere-ocean model Kay et al. (2018) and computed annual averages for ICES (International Council for the Exploration of the Sea) statistical rectangles in the North Sea region that have a spatial resolution of one-degree longitude and 0.5-degree latitude.

Further, we explored temporal stock dynamics of plaice in the North Sea based on time series (1957 – 2019) of spawning stock biomass (SSB) and fishing mortality (F) derived from routine stock assessments (ICES, 2019a). With the help of catch per unit of effort (CPUE) data, collected by the International Bottom Trawl Survey (IBTS), we analysed spatial stock dynamics in the entire German EEZ and separately for inshore and offshore areas. We refined the SES spatial boundaries in more detail through the spatial analysis of logbook data with available information on landing ports (2009 – 2019).

Actors

Plaice is mainly caught by two German fleets, one using beam and pulse trawls to catch demersal fish, i.e. plaice, sole or turbot (Scophthalmus maximus), and a second us-

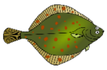
Tier1	Tier 2	Indicators
Resource system 	Clarity of system boundaries	Spatio-temporal allocation of fishing activities; Location of landing ports
	Predictability of system dynamics	Yearly SST (C°)
	Productivity of system	Annual landings (t) by species
Resource unit 	Growth or replacement rate	Annual spawning stock biomass (SSB) of plaice (t)
	Interaction among resource units	Annual total catches of plaice (t), Fishing mortality (F)
	Spatial and temporal distribution	Relative spatio-temporal changes of plaice catches in the southern North Sea
Actors 	Number of relevant actors	Annual catch compositions per metier, number of fishing trips per year and metier, number of vessels per year and metier
	Socio-economic attributes	Average length (m) of fishing vessels per fleet; Average annual income (€), costs (€), profit per vessel (€); Average annual price (€) of target species, Average annual price of oil ($), Average annual number of engaged crew and Full Time Equivalent (FTE) per vessel; Age of the fleet (y); Number of companies and producer organisations to which the vessels were associated to
	Spatial and temporal distribution	Relative spatio-temporal changes of plaice catches in the southern North Sea
	Importance of resource (dependence)	Spatiotemporal changes in centre of gravity of plaice catches of German vessels
	Socio-cultural attributes	Description of fishing culture and culture barriers to adaptation
Governance System 	Description of fisheries assessment and management system	Mapping governance structures and decision-making process

Table 3.1: Domains (Tier 1) and components (Tier 2) of the German plaice related fisheries social-ecological system in the southern North Sea following the specifications of (McGinnis and Ostrom, 2014) together with the respective indicator, metric and assessment methods.

ing otter bottom trawls to catch mixed demersal species such as plaice, Norway lobster (Nephrops norvegicus), and turbot (STECF, 2019). Some fishing vessels switched target species and respective gears within a year making the categorisation of fishing fleets difficult. For this reason, we categorised all German vessels as fishing métiers based on logbook data for individual fishing trips (between 2000 to 2019). Logbook data included landings (tonnes), deployed gear, date and time, as well as the geographical location at ICES rectangle resolution (0.5° lat × 1° lon) (provided by the German Federal Office for Agriculture and Food). For each vessel we determined the relative catch composition per fishing trip. Based on the ten most caught species, we created a Euclidean distance matrix and performed hierarchical agglomerative clustering using the complete linkage approach (Legendre and Legendre, 2012). Due to the large number of fishing trips (n = 140633), we divided the data and clustering into three randomly selected subsets. For each random set we named the respective cluster after the dominant species and explored its spatial distribution. After visually examining the catch composition and geographical distribution for each cluster we merged matching clusters (i.e. the métiers) resulting in seven final clusters. We calculated the number of SES actors as the number of vessels associated with each métier and analysed the temporal trends of the relative catch composition of all seven métiers.

Furthermore, we extracted socio-economic attributes of the actors from logbook data and the German vessel register (not publicly available) comprising the length of vessels (m) and the companies or producer organisations to which vessels belonged that catch at least 50% of plaice and sole.

For the two types of vessels (beam or otter trawlers) that could be associated with the here defined métiers, we extracted from the Scientific, Technical and Economic Committee for Fisheries (STECF) data base (www.stecf.jrc.ec.europa.eu) (2008 – 2018) the average income (€), cost (€), investment (€), engaged crew members, and full time equivalent (FTE) per vessel. We furthermore assessed temporal trends of average annual prices (€) of target species from STECF and Brent crude oil prices ($) from world bank data base (www.data.worldbank.org).

We described the SES actor's attribute "importance of the resource or dependence on the resource" (see Table 3.1) by assessing spatio-temporal changes of plaice landings of German vessels by means of centre of gravity analysis (He et al., 2011). This is used as a proxy of the technical capability of German vessels to adjust their operations to the resource distribution. We calculated the centre of gravity as the mean (geographic) centre of ICES rectangle midpoints weighted by the landings derived from annual logbook data (2000 – 2019) (Engelhard et al., 2011).

Maintaining a socio-economically and socio-culturally viable fishery within spatially refined boundaries requires the SES actors to adapt their fishing strategies to changing environmental and socio-economic conditions. Therefore, we analysed such changes in strategies of the German plaice related fisheries by using network analysis. We use network metrics to quantify the yearly averaged connectivity between fishing trips of individual vessels being associated to a specific métier (Frawley et al., 2021) (Appendix 3.A). The degree of connectivity is higher the more a vessel participates in a pair of métiers, which additionally indicates higher resilience against changes in a SES (Frawley et al., 2021; Fuller et al., 2017).

Finally, we conducted a qualitative interview-based study with fisheries representatives to understand both the nature and changes of socio-cultural attributes of fishers and the fishing community, as well as barriers to adaptation as perceived by the German North Sea fisheries. Initial background interviews provided a first overview of issues from the perspective of people involved in the sector. Subsequently, detailed qualitative semi-structured interviews were conducted with a set of individual fishers (N=18) and trainee fishers (N=30). Due to the Covid-19 pandemic most of these interviews were online. Their focus was on key aspects of self-perception and understanding of fishing as a job and a lifestyle, comprising: 1) values, lifestyle, knowledge and traditions; 2) the practice of fishing and what makes a person a "good fisher"; 3) perspectives of older and younger generations and changes over time; 4) past and future challenges to fishers from the perspective of those active in fishing; and 5) self- organisation, political representation and fishers' view on policies affecting them in their fishing activities.

Governance Structures and Decision-Making Processes

Fisheries management in a European context is a multi-level governance system with legislative and executive bodies implementing policies and decision-making processes. These in turn are driven by European directives and policies based on the Common Fisheries Policy (Belschner et al., 2019; Van Hoof and Kraus, 2017) and implemented by EU Member States through national and local legislation and policies. In addition, other policies, formulated independent from fisheries policy (e.g. MSPD, MSFD), are highly relevant for spatially allocating fishing activities, in particular those leading to spatial constraints such as the development of offshore renewables or implementations of European environmental policies entailing marine protected areas (Probst et al., 2021). To illustrate the multi-level hierarchy in the decision-making processes to which the SES is exposed, we translated the EU process on defining quota and catch limits by the EU (https://www.consilium.europa.eu/en/infographics/fishing-opportunities-infographics) together with the additional governance components into a swimlane diagram of the decision- making process. With the help of the above described interviews we mapped stakeholder's perception of the prevailing governance processes. These formed the basis to discuss barriers to SES adaptation in relation to management decision making processes.

3.3 Results

3.3.1 Spatio-Temporal Dynamics of Resource System and Unit

The resource system as such, comprising also the wider North Sea, has experienced a clear warming trend of approximately 0.5 °C since the mid-1990s (Appendix 3.B). Highest annual average temperatures were observed in the 2010s in the middle of the study area (Appendix 3.B). The key resource unit, North Sea plaice, experienced a strong recovery from a depleted state during the late 1990s to record high spawning stock biomass in recent years, exceeding all recently applied biomass reference points (Fig. 3.2 a). Plaice recovery is clearly a result of a drastic reduction in fishing mortality from above 0.6 in the 1990s to below all reference points and especially the management target of FMSY=0.21 (Fig. 3.2 b) (Blöcker et al., in press). However, the increase in the North Sea plaice stock is not spatially homogeneous (Fig. 3.2 c). Stock components strongly increase in the north of Scotland as well as in the offshore areas of the Netherlands, Germany and Denmark. Within the German EEZ and surrounding waters the increase was observed until 2011 only, while afterwards the offshore stock component declined to the low levels of the 1990s (Fig. 3.2 d). Importantly, the coastal stock component of the German

EEZ did not increase but decreased (Fig. 3.2 e, f). The observed spatio-temporal trends suggest a general decoupling of the plaice stock dynamics between the greater North Sea and within the German EEZ, and a drastic decrease in the coastal stock component. The spatial boundaries of the resource system, based on plaice landings by the German fisheries, were stable over time and most productive coastal fishing grounds were observed within the Dutch, German and Danish waters (see Appendix 3.C). German vessels landed plaice primarily in the Netherlands and Denmark, with Dutch ports such as Harlingen, Den Helder, and Louwersoog. Louwersoog is the most important port because since 2009 at least 75% of the German catches have been landed there.

3.3.2 Spatio-Temporal Trends of Actor Attributes

Catch Composition of Defined Métiers and Number of Actors

The temporal trends of the productivity of the system, i.e., the annual changes in catch composition of each métier, is shown in Appendix 3.D. Three North Sea métiers were characterised by plaice catches, namely the Nephrops & Plaice (NP), the Plaice (P), and the Plaice & Sole (PS) métiers, respectively. The NP metier is composed of demersal trawlers catching mainly Norway lobster and plaice. The P metier is also dominated by demersal trawlers catching plaice. In contrast, the PS métier refers to beam trawlers catching mainly plaice and sole (Figure 3.3). In all métiers plaice catches dropped significantly in 2007, increased slightly afterwards and decreased again since 2016 (Appendix 3.D). At the same time sole catches increased. For the NP métier, plaice catches were rather low between 2000 and 2006 and increased to a relative contribution of roughly 30% to the total catch in 2019. In contrast, Norway lobster catches increased continuously over the past twenty years contributing now up to approx. 50% of the total catch (Appendix 3.D).

The number of actors actively engaging in fishing, and hence the number of fishing trips and vessels associated with the plaice-related métiers, has changed greatly over the past two decades (Figure 3.4). From 2000 to 2006 the overall number of vessels decreased from 180 to approx. 100 and the related number of annual fishing trips declined continuously from 1800 to 800. In line with the observed decreasing trends in plaice catches (Appendix 3.D), the total number of fishing trips dropped sharply in 2007 and remained stable

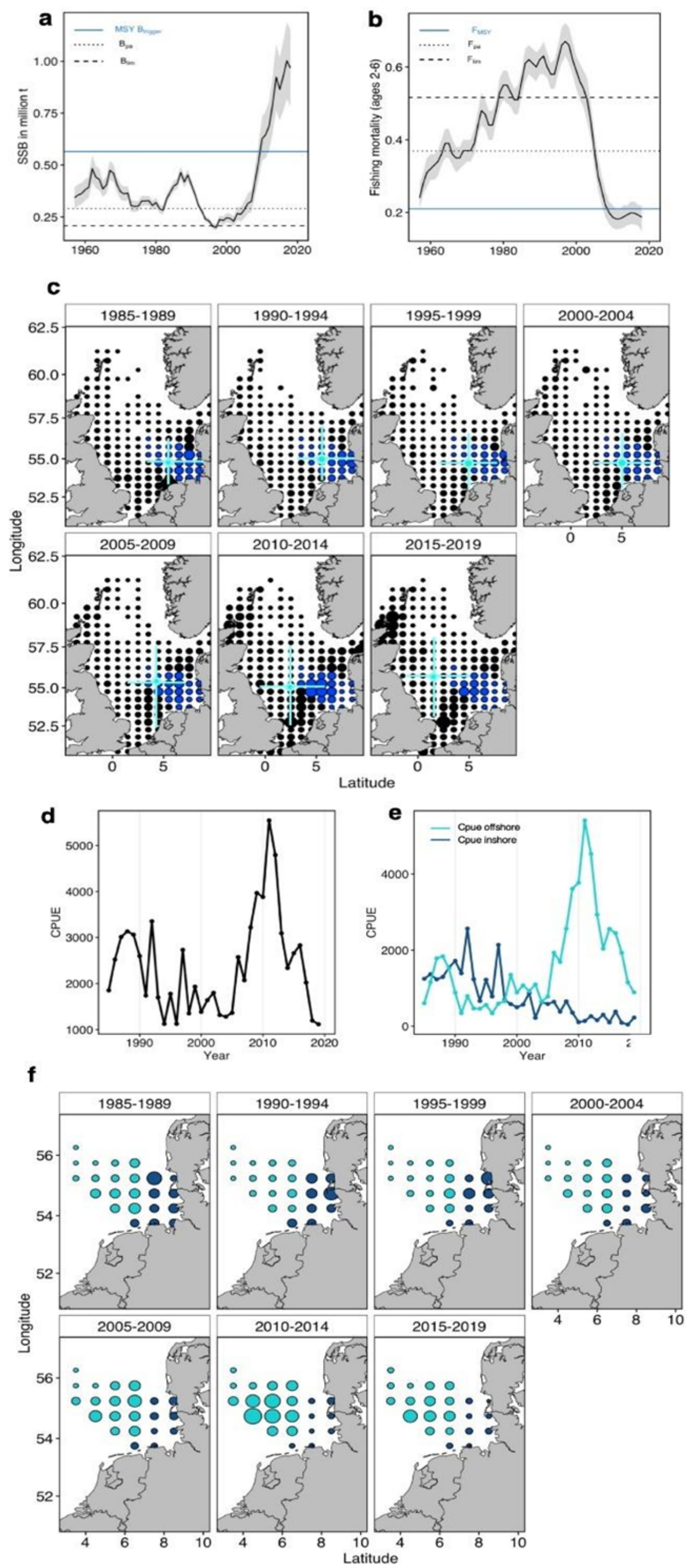


Figure 3.2: Temporal development of the North Sea plaice a) spawning stock biomass (SSB) and b) fishing mortality - grey shaded areas represent confidence intervals; horizontal lines indicate management reference points. Spatial changes in 5-year average cpue in the entire North Sea - the turquoise cross indicates the centre of gravity of the stock; blue dots represent cpue in the German EEZ (see f); temporal development of plaice stock in the entire German EEZ and coastal waters (d), and divided in inshore (blue) and offshore (turquoise) areas (e); spatial changes in 5-year average plaice cpue in the German EEZ.

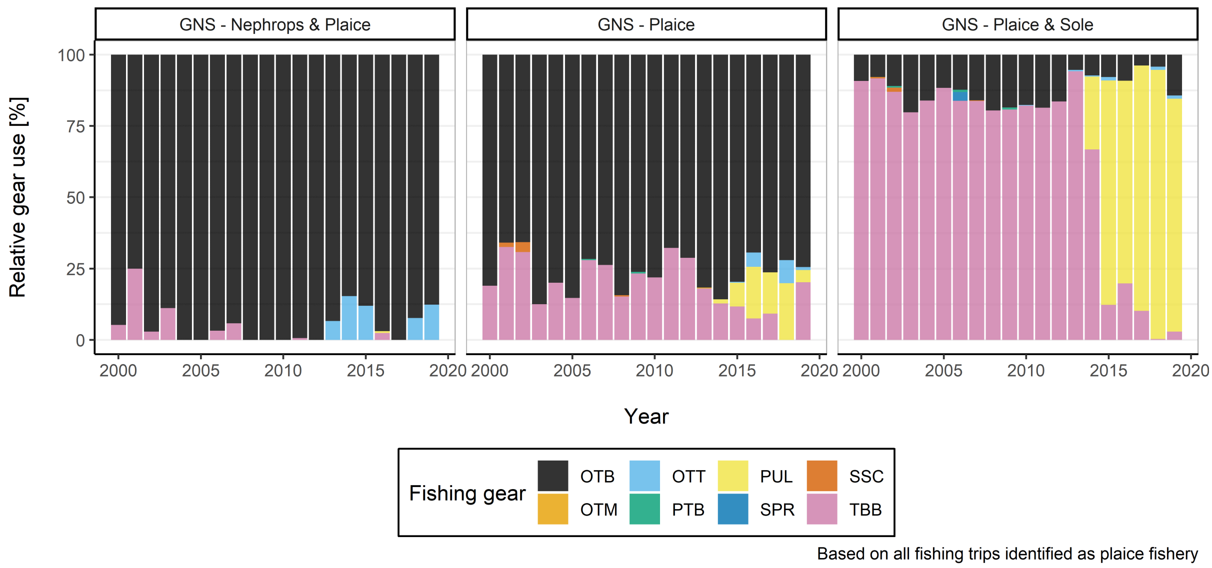


Figure 3.3: Relative composition (%) of gears deployed across all annual fishing trips in the greater North Sea (GNS) associated to the GNS - Nephrops & plaice, GNS - Plaice & Sole, and GNS - Plaice métiers. OTB: bottom otter trawl; OTM: Midwater otter trawl; OTT: twin bottom otter trawl; PTB: bottom pair trawl; PUL: pulse bottom trawl; SPR: Danish seine (anchored); SSC: Danish seine (without anchor); TBB: beam trawl.

afterwards. Annual fishing trips and vessel numbers of the NP métier increased from 2006 onwards, however not compensating for the decline of the overall fleet size.

Socio-Economic Actor Attributes

Over time we found a constant average vessel length of 24m for the NP métier, while the vessel length increased from 2015 onwards for the PS and P métier (Appendix 3.E). This increase coincided with the successive replacement of beam trawls by pulse trawls (Figure 3.3). The number of ship owners decreased over the past 20 years from 35 to 10. In terms of producer organisations, the majority of vessels belonging to some form of organisation are members of just one fishery cooperative. Its membership increased by roughly 30% since 2000, while membership in all other organisations markedly decreased over the same period. To date, there are no other organisations and only a minority of the vessels are self-organised (owner operators).

The average income, costs and profit of beam and demersal trawlers engaging in the plaice related fisheries increased from 2008 to 2018 (Figure 3.5). A key characteristic for these vessels, which mostly operate offshore, is that their income has been almost exclusively generated from landings, while other sources of income such as owning restaurants

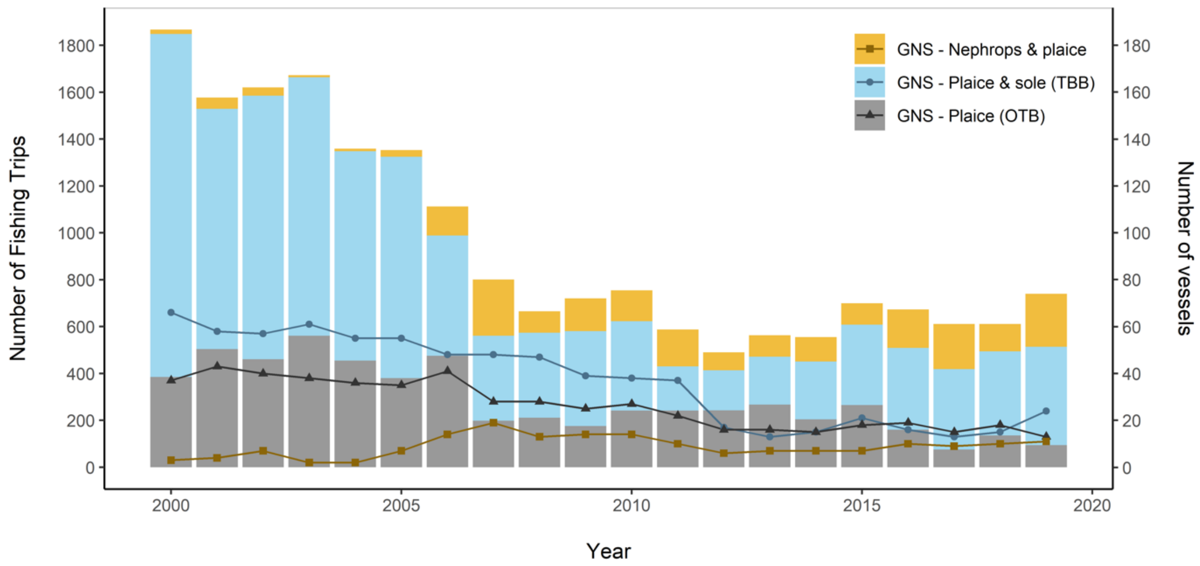


Figure 3.4: Annual number of fishing trips (bars) and number of vessels (lines) associated to the métiers Nephrops & plaice (yellow), Plaice & sole (blue) and Plaice (grey). Note that within one year a single vessel might have been associated to more than one métier since the allocation is based on individual fishing tips and catch compositions.

or conducting charters seemed not relevant. The observed increase of the average annual income and profit has mainly two reasons. Firstly, these vessels could be associated to more than one of the métiers defined here which means a changing catch composition (Appendix 3.D) over time with reduced plaice catches but increasing Norway lobster or sole catches. Since the prices per kilo for sole and Norway lobster were 3 to 5 times higher than that of plaice (Figure 3.5), the overall income and profit increased. In addition, the drop of oil prices in 2008 and 2016 contributed to increased profits (Appendix 3.F). As opposed to the annual average working hours and number of engaged crew per vessel, which remained relatively stable over time (Figure 3.5).

Besides the observed changes in catch composition and socio-economic attributes the overall importance of plaice as a key SES resource unit is reflected in the persistent spatial patterns of German plaice catches (Appendix 3.C). The annual centre of German plaice catches remained mostly within the German EEZ of the North Sea, while the centre of gravity of UK plaice catches followed the northward shift of the resources. The greatest distance between two centres was observed to be 95 km between 2005 and 2014.

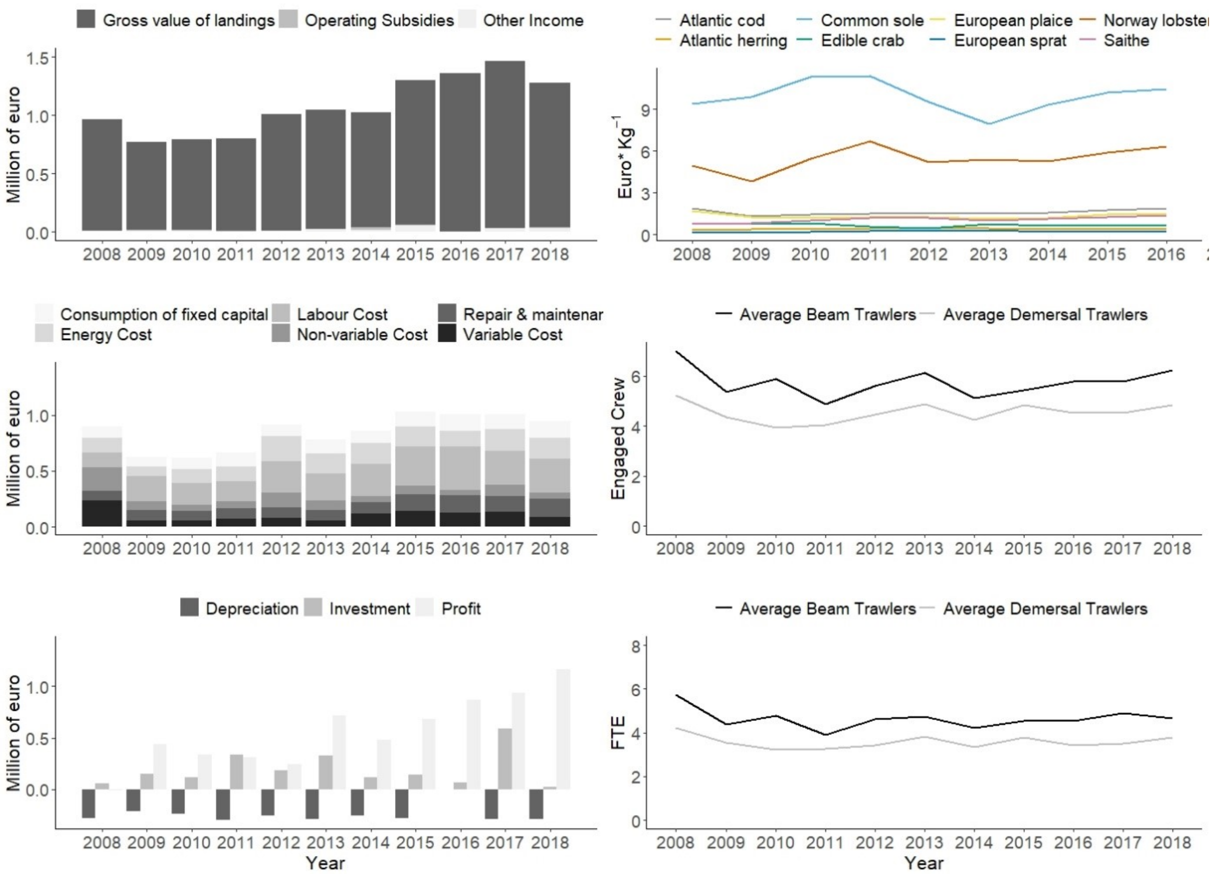


Figure 3.5: Socio-economic attributes of actors. The upper panel shows the average annual income (upper left), costs (upper middle), and profits (upper right) of German beam and demersal trawlers engaging in the plaice related fisheries; the lower panel shows the annual average fish prices (lower left), number of engaged crew (lower middle) and the full-time equivalents (FTE; lower right)

Changes in Fishing Strategies

We explored changes of fishing strategies for the fishing métiers defined here in the Greater North Sea and Baltic Sea with the help of network connectivity metrics based on individual fishing trips (Figure 3.6). The higher the connectivity between a pair of métiers, the more often a respective vessel participated in both métiers. Vessels participating in a métier with a high level of connectivity can be described as generalists whereas a low level of connectivity refers to a more specialised fishery. Overall, we found a general decrease of connectivity over time, indicating a potential decrease of the adaptive capacity of vessels to switch between fishing practices (Appendix 3.A). Our results showed a declining level of connectivity between the Baltic Sea and Greater North Sea fisheries between 2005 and 2014, which grew stronger again only in recent years. The five-year averaged networks of the different métiers showed that the plaice métier (P) and PS métiers both played a central role in connecting fisheries within the Greater North Sea, whereas the P métier was also connected to the cod fisheries in the Baltic Sea. In the later years, the NP métier moved towards the centre of the Greater North Sea network and even played a cross-regional role from 2010 onwards. A comparison of individual métiers revealed that before 2006 connectivity was highest for the PS metier (Appendix 3.A, Figure 3.9). Thereafter the connectivity of the three métiers (PS; NP; P) showed comparable orders of magnitude. On the contrary, the relative connectivity strength of the NP métier increased over time, although it always remained below the connectivity strength of the PS métier. This indicates that in recent years the NP métier seemed to have the highest potential to adapt, hence to change fishing strategies.

3.3.3 Governance Structures and Decision-Making Processes

The EU linear decision process for setting quota is shown in Figure 3.7 together with the multi- level governance system to which the SES is exposed. Thus, most fish stocks such as plaice in the North Sea are mainly managed through a quota system based on total allowable catches (TACs) for participating countries. Annual TACs of plaice are based on stock assessments carried out within ICES by international fisheries experts as well as advices from STECF. Final decisions on TACs, prepared by the European commission based on input from ICES and STECF, are made annually through negotiations

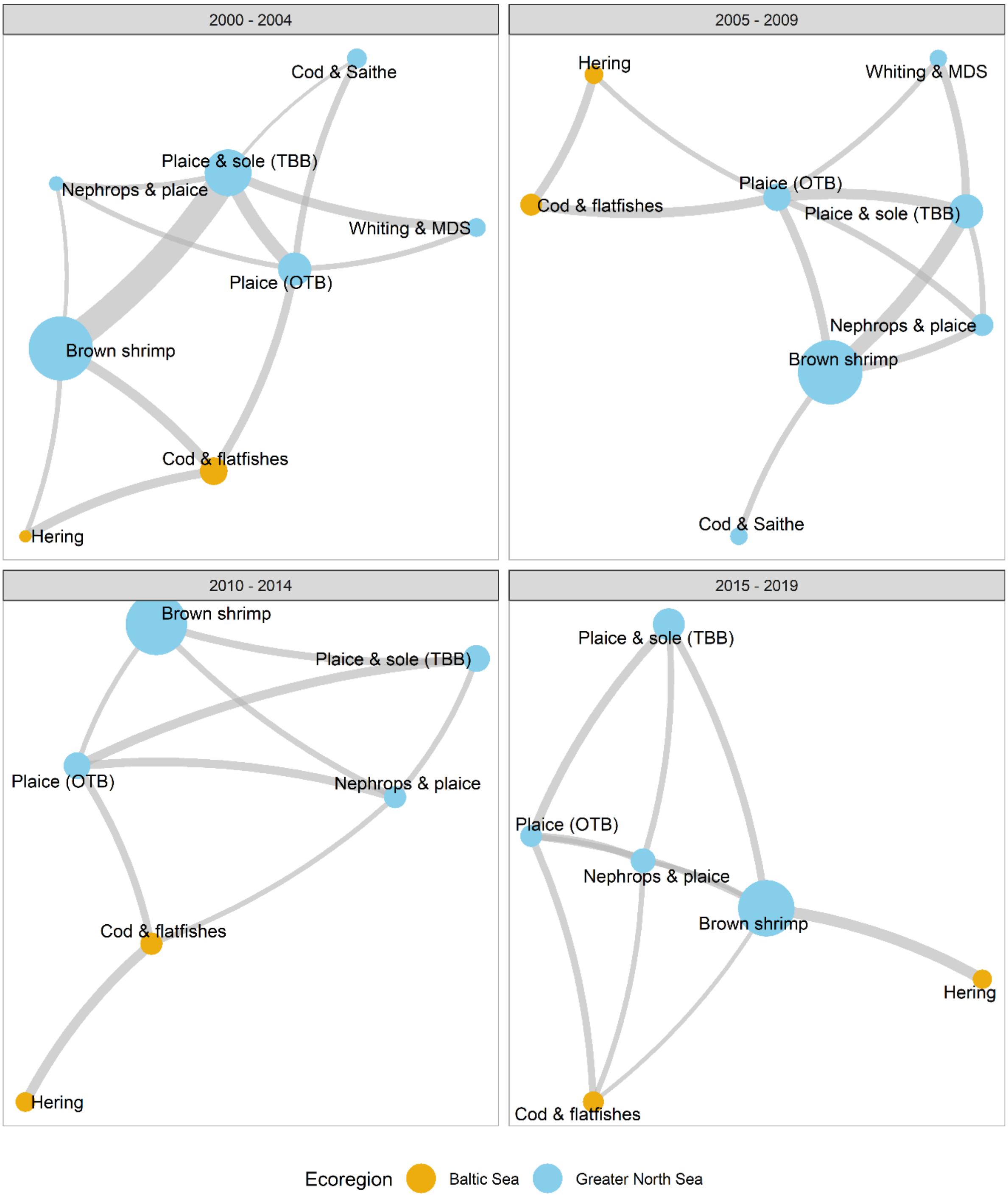


Figure 3.6: Undirected networks showing the connectivity between the different métiers in the North Sea and Baltic Sea. Node size represents the average number of annual fishing trips of the respective métier and edge size represents the connectivity between métiers based on averages of annual edge weights. The larger the node, the more numbers of fishing trips. Thicker edges indicate both more vessels participating in the respective pair of nodes, as well as more even distribution of their fishing effort among the pair of nodes.

in the European Council of the fisheries ministers (see Figures 3.7 and 3.8). The lower part of Figure 3.7 depicts the national process where the quota allocations are further managed and distributed on a national basis by the respective ministry. Further spatial fisheries restrictions are also related to governance processes, which are not related to the EU fisheries policy implementation. Spatial restrictions are rather related to EU environmental policies and national MSP processes which govern for instance the spatial expansion of offshore renewables. Our stakeholder interviews confirmed the "receiver" position of the fishing sector in this decision process (Figure 3.8). With respect to quota allocation our interviews highlighted that the national allocation of TACs in Germany, based on tradition and historical catches per vessel is as often regarded as unfair and restricting. Furthermore, the EU discard ban complicates their planning because TACs for bycatch species might be required in addition to the main species. The discard ban aims at balanced harvest and should support a more selective fishery (Borges, 2021). The same is the case for the so- called choke species problem, where a species with a low quota can cause a vessel to stop fishing even if they still have quota for other species. Overall, fishers and fisheries sector representatives perceive spatial exclusion from their traditional fishing grounds due to competing marine uses such as offshore renewables and the implementation of fishing restrictions in marine protected areas as the most significant future challenges. These policies affecting the SES are developed independently from the CFP in separate processes stimulated by EU Directives and are completely under national planning jurisdiction (Figure 3.7). While fishery representatives are involved as stakeholders in these policy processes, fisheries interests do not feature prominently in their legislative objectives. Interviews with fisheries representatives and public and parliamentary debates on the future development of the German EEZ furthermore highlight that fishing is neither a major nor powerful actor compared to shipping, energy, and nature conservation (Figure 3.8).

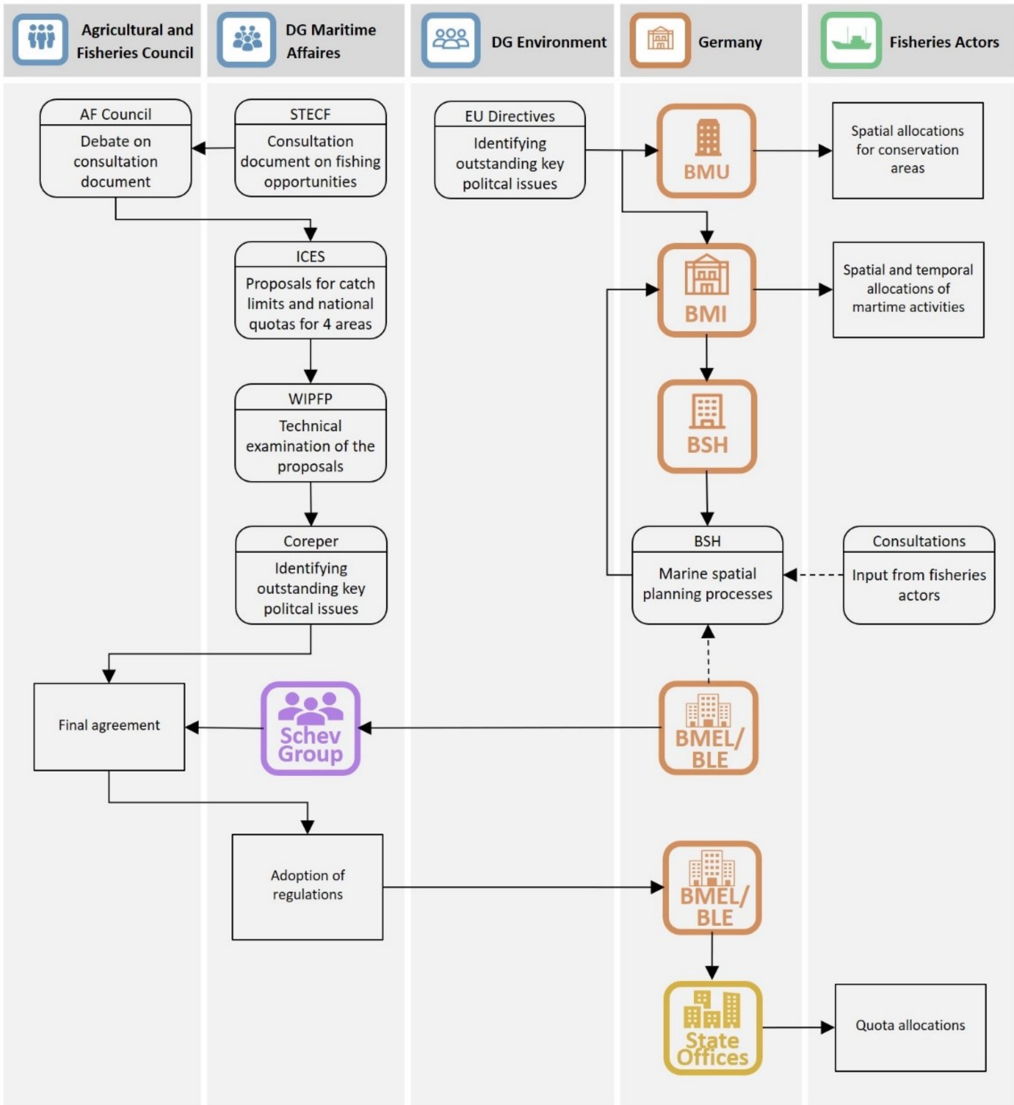


Figure 3.7: Linear representation of the multi-level hierarchy in the decision-making process relevant for the SES.

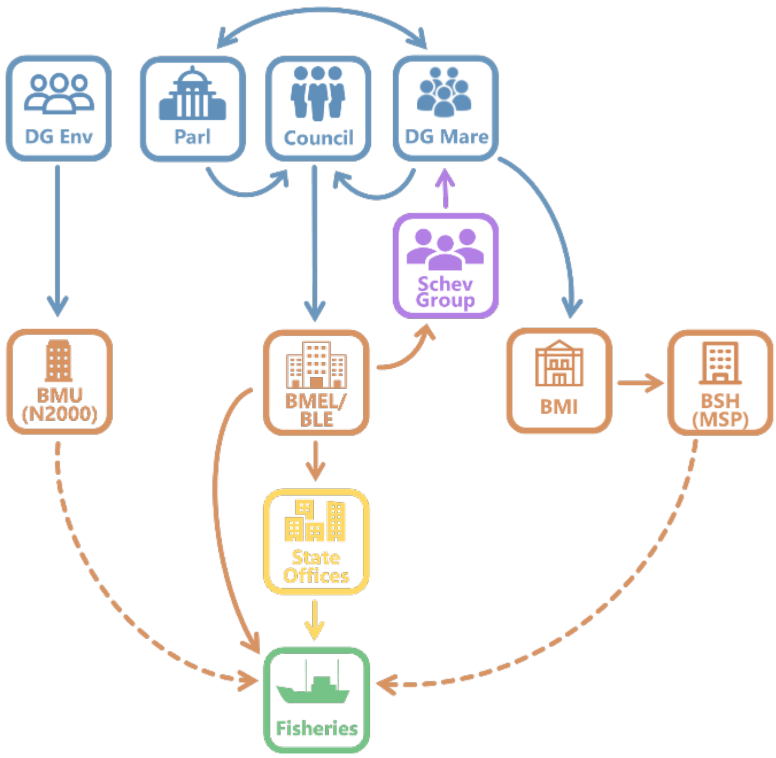


Figure 3.8: General structure of the governance system related to the German fishery sector.

3.4 Discussion

3.4.1 Unravelling Autonomous SES Adaptation

Fisheries SESs must continuously adapt to both environmental and socio-economic change that impact the structure and function of the SES in which they are embedded (Frawley et al., 2021). Only recently, research on fisheries SESs quantified adaptive capacities towards, e.g., environmental change (Bograd et al., 2019; Brattland et al., 2019; Silva et al., 2019; Thiault et al., 2020). Many empirical studies analysed fisheries SESs at rather small geographical scales describing the state, regulation and use of a single biological resource (Lauerburg et al., 2019). Our study is one of the first that quantified the spatio-temporal dynamics of SES attributes at larger spatial scales involving more than one resource. Combining the Ostrom framework with quantitative and analytical approaches (Schlüter et al., 2012) enabled an in-depth understanding of the factors that determine SES dynamics.

The decrease in plaice catches in 2005 caused a direct socio-economic change, such as an increased activity of the Nephrops & Plaice métier and a shift of the main gear deployed by the Plaice & Sole métier. Hence, interviews confirmed that many coastal fishers have abandoned near-shore flatfish fisheries (switching to brown shrimp fishery) in response to the shift of plaice to more northern offshore waters, where the resource is now out of reach for their small vessels. In summary, we found a rather rapid autonomous adaptation of the SES actors to declining plaice catches over the past 20 years based on technical innovation such as pulse trawls leading to increased sole catches, catch diversification and a change in fishing strategies. The deployment of pulse trawls, which are known for a higher sole catch efficiency (Rijnsdorp et al., 2020), allowed the SES actors to move to different areas previously not accessible by the heavy beam trawl (Hintzen et al., 2019). However, pulse trawling in EU waters was banned in 1998 and re-introduced in 2006 (Le Manach et al., 2019), but has been banned again from 2021 onwards. Our results confirmed a general increase of higher priced sole and Norway lobster catches over the past ten years. In part, the combination of low fuel costs, decreasing number of vessels and fishing trips caused an increase of profits for the remaining vessels. The decreasing connectivity of métiers over time, revealed a trend towards specialisation and a likely reduction of the ability to switch fishing strategies, emphasising a potential diminution of the overall capacity of the SES to adapt to global change.

3.4.2 Barriers to Adaptation

Our analysis revealed consistent SES system boundaries over the past 20 years and a strong link between the resource unit plaice and the SES actors. Target species and the respective catch compositions showed clear fluctuations, with a constant decline of plaice catches over time within the system boundaries. Interviews revealed that the observed spatial persistence of fishing patterns, despite decreasing catches, might be rooted in the fishing culture and self- perception of fishers. Hence, our observations confirm the fact that professional fishing can appear to persist against the odds (Christy et al., 2021), which is linked to the choice of fishing as a lifestyle rather than an ordinary job. Success and standing within the community are closely linked to the size of the catch, making competition and a degree of rivalry between the fishers a key element of the prevailing fishing culture. Our interviews confirmed that independent of specific fisheries and métiers, most German fishers tend to define themselves as fishers in the sense of actively fishing rather than economic entrepreneurs; most are not interested in engaging in the marketing or selling of fish.

We recognised that the main barriers to adaptation arose from the commercial environment of the fishers and their concerns over future spatial and environmental policy. Fishers know the inherent need to be flexible and that the profession has always adapted to change, but current uncertainties (e.g. Brexit, increasing competition with the fleets of neighbouring countries or the effects of rising fuel prices) resulted in a low affinity to "risk appetite" (such as investing in new boats or gear). Our findings show that business structures per se and more so in neighbouring countries have changed from small family businesses to more organised cooperatives and more industrialised fleets. Given that German fishers are mostly interested in fishing, there is little interest in forming cooperatives or developing alternative, more localised marketing strategies that could help increase profitability.

There is also no real intent to become involved politically, although existing structures are criticised for their lack of effectiveness in giving fishing in Germany a greater voice. In summary, fishers do regard their current situation as requiring change. The greatest barrier to adaptation seems to be a mindset that sees fishers as trapped by compounding factors – by an unfavourable regulatory environment, by spatial shifts in the resource, by the perceived lack of political support, the inability to make the necessary financial investments (in vessels and gear), and the inability to organise the necessary changes (obtaining support for risk-taking, self-organisation, professionalisation of tasks such as marketing) from within the community itself.

The CFP is the key policy driving the governance processes regarding fisheries at the EU and German scales. However, we conclude that national interpretation and process of implementation defines the specific outcome for fishers. For the here studied SES, it is primarily the MSPD and associated sectoral policies that regulate the introduction of spatially exclusive maritime activities such as offshore renewables, hence creating vulnerabilities in terms of displacement and limiting the access of the fishers to fishing grounds (Stelzenmüller et al., 2022). A detailed impact assessment of the multi-level governance system described here for the adaptive capacity of the German southern North Sea fisheries to e.g. environmental and socioeconomic change, is largely beyond the scope of our study. However, we took a first step towards a better understanding of the role of governance in enhancing the adaptive capacity of our SES by mapping the complexity of governance structures and its major components.

3.4.3 Future Management Needs to Support SES Adaptation to Global Change

Our study strongly supports the conclusion that SES adaptive capacity builds on the experience and knowledge of community members (traditional ecological knowledge) to characterise pertinent conditions, community sensitivities, adaptive strategies, and decision-making processes (Cinner et al., 2018; Smit and Wandel, 2006). An in-depth assessment of adaptive capacities requires not only collaboration across traditionally distinct disciplines and sectors (Friedman et al., 2020). More importantly, it necessitates access to the knowledge of the communities associated with the resource system and the subsequent selection of indicators and data (Lauerburg et al., 2019; Sterling et al., 2017).

Applying the multi-tier framework required the integration of a multitude of data sources and analytical approaches ranging from stock assessment, network analysis to qualitative interviews. Our analysis does not allow us to conclude on optimal, robust, or adaptive management strategies that take uncertainty, different time scales, and nonlinear behaviour of SESs into account. The evaluation of management and policy strategies would require ecosystem models (Steenbeek et al., 2021), modelling frameworks (Oliveira et al., 2022) or integrative probabilistic modelling approaches such as Bayesian belief networks (Rambo et al., 2022). Nevertheless, our approach does allow for a general characterisation and deeper understanding of autonomous SES adaptive capacities.

With the help of the multi-tier Ostrom framework we have described the autonomous or reactive adaptation of the SES and extracted the barriers of adaptation for SES actors comprising also the multi-level governance system to which the SES is exposed. SES actors or fishers are in the "receiver" position at the bottom of the decision-making process. Hence, they do not play a direct role in the decision-making process, limiting the potential to adapt. This shows that one of the key design principles illustrated by long-enduring common-pool resource institutions - "Individuals or households with rights to withdraw resource units (e.g. fishers) are clearly defined" (Basurto and Ostrom, 2019) is neglected. We argue that when environmental change is coupled with external and socio-economic change and when governance does not acknowledge design principles of common-pool resources (Gari et al., 2017), the SES adaptive capacity potential decreases and may reach its limits. This situation corresponds to a social-ecological trap in which social and ecological feedbacks reinforce one another locking a SES into an undesirable state (Eriksson et al., 2021; Villasante et al., 2022). According to Boonstra et al. (2016), social-ecological traps emerge from multi-scalar processes, and structural drivers which often originate outside the local scale or community reflecting the values and influence by other interests. Among the three pathways for disrupting socio-ecological traps described in Eriksson et al. (2021), co-management is the one that would have the highest potential to strengthen the SES adaptive capacity.

Within the spatial boundaries of the SES, co-management needs and approaches should be tailored to the local context. We postulate that co-management should relate to all decision- making processes affecting the SES: fisheries management, marine conservation and MSP. For instance, tailored co-location solutions for offshore renewables and fisheries could mitigate the loss of fishing opportunities and should be explored and facilitated through MSP and licensing (Stelzenmüller et al., 2022). Such co-location solutions could contribute to diversification of catches, fishing practices and possibly livelihoods (Stelzenmüller et al., 2021). Strengthening co-management approaches would also follow the growing recognition that fisheries should be managed for all three pillars of sustainability: economic, social and environmental sustainability (Garlock et al., 2022), implying a proper recognition of fishers' self-perception and socio-cultural as well as economic conditions. Recent studies suggested measures to enhance SES adaptive capacity, comprising fisheries diversification, access to resources, alternative management or licencing systems as well as general coping strategies of fishing communities (Frawley et al., 2021; Jara et al., 2020; Silas et al., 2020; Thiault et al., 2019b). To strengthen SES adaptive capacity in the southern North Sea, where coastal communities and fishing fleets have generally a higher risk of adverse consequences due to climate change (Payne et al., 2021), we in particular stress the necessity of alternative management from the above list of measures. A shift from a multi-level governance system to a more bottom-up community centric decision-making process is needed for SES to withstand external factors such as climate change induced ecological tipping points, market trends and strong fluctuations of operating costs.

3.A Network Connectivity

First, we calculated the total and relative sums of trips per métier, vessel, and year. To focus on the dominant métiers, we removed data points with less than ten trips, as well as less than 10 % of the total trips per vessel and year. We measured the connectivity between two fisheries for each year using an adapted formula of (Fuller et al., 2017) in which we replaced revenue of vessels by number of trips, since revenue data were only available from 2009 onwards. Hence, we computed annual undirected networks and weighted edges according to connectivity values between two fisheries. We assessed our networks by calculating node strength and edge density. Node strength (the sum of numbers of fishing trips per métier of all edges pointing to one node) is a proxy of how métiers are connected to each other. Edge density is an indicator for the connectedness of a network, which is calculated as the sum of all edge weights divided by the sum of all node weights and (Frawley et al., 2021; Fuller et al., 2017). Further we averaged node strength to represent the weighted connectedness of a network. Both metrics are indicators for the connectedness of the network, and, in networks of participatory fisheries, may be used to determine the resilience of fishery (Frawley et al., 2021; Fuller et al., 2017). A higher connectedness usually means a higher adaptive capacity of the fishers, because, in case of rapid change leading to an exacerbation of a fishery, they can more easily switch to another fishery.

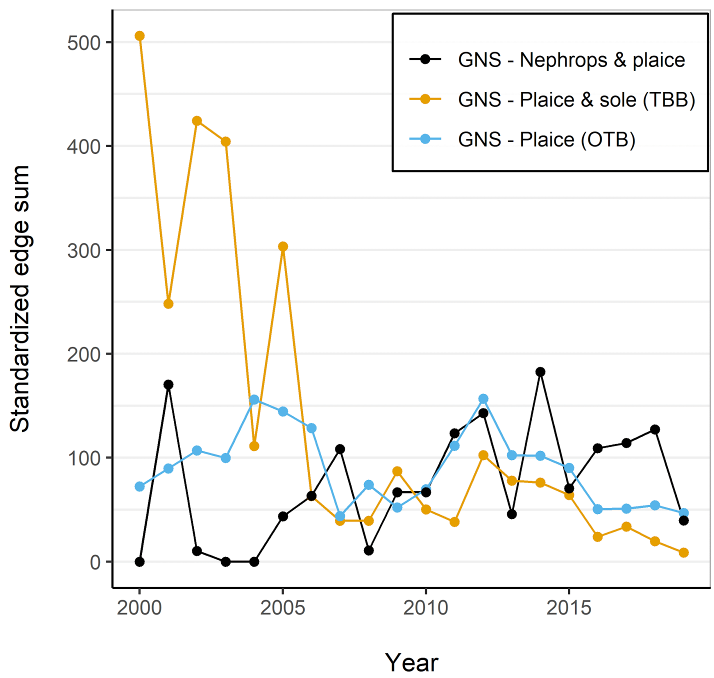


Figure 3.9: The sums of all edge weights connected to respective métier nodes standardised by the number of vessels participating in that respective fishery each year.

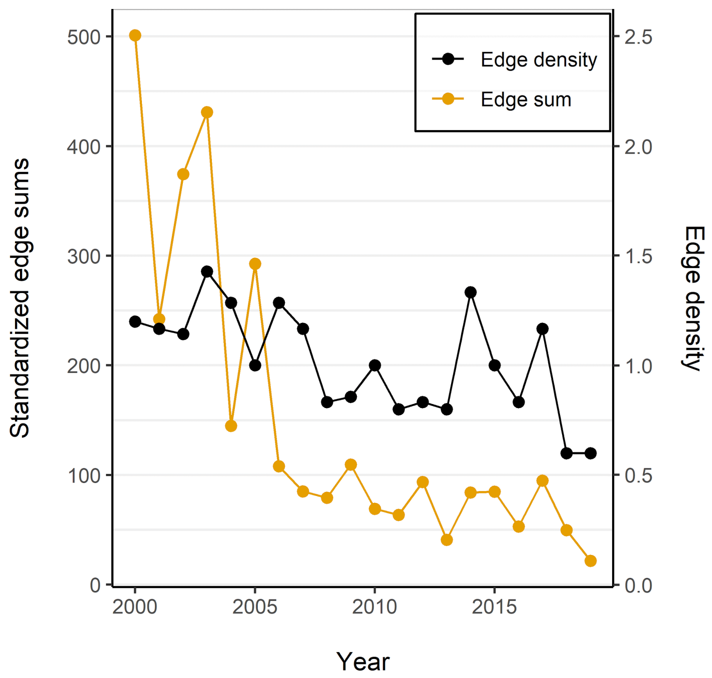


Figure 3.10: Standardised edge sum and edge density are network metrics and proxies for the connectivity of the network. Standardised edge sum depicts the yearly sum of all edge weights divided by the number of vessels active in that respective year. Edge density is the number of edges divided by the number of nodes (fisheries).

3.B Sea Surface Temperature

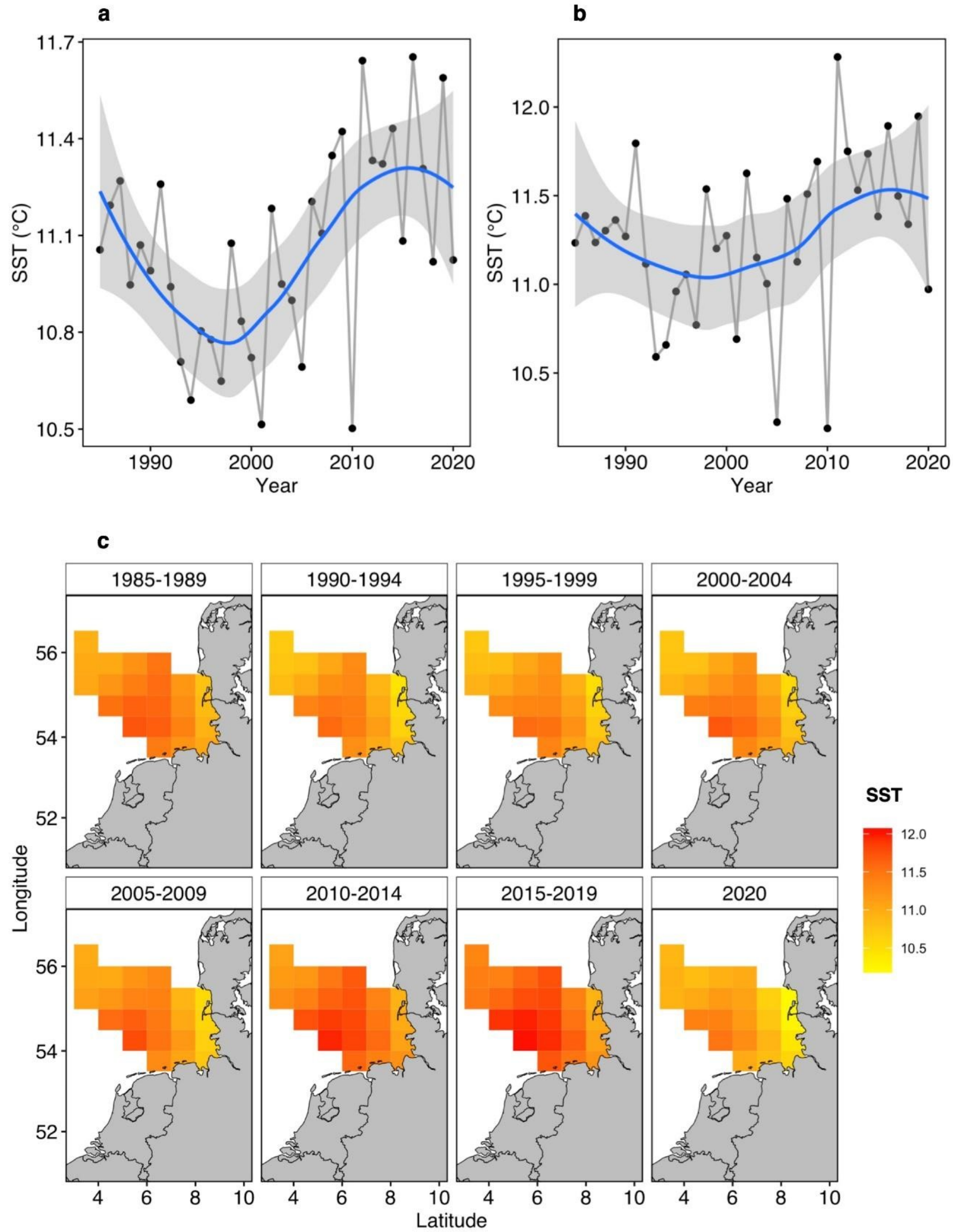


Figure 3.11: Temporal changes in average sea surface temperature (SST) in the greater North Sea (a) and in the German Exclusive Economic Zone (EEZ) and coastal waters (b) - blue lines represent a loess smoother; spatial changes in 5-year average SST in the German EEZ and coastal waters (c).

3.C Plaice Landings

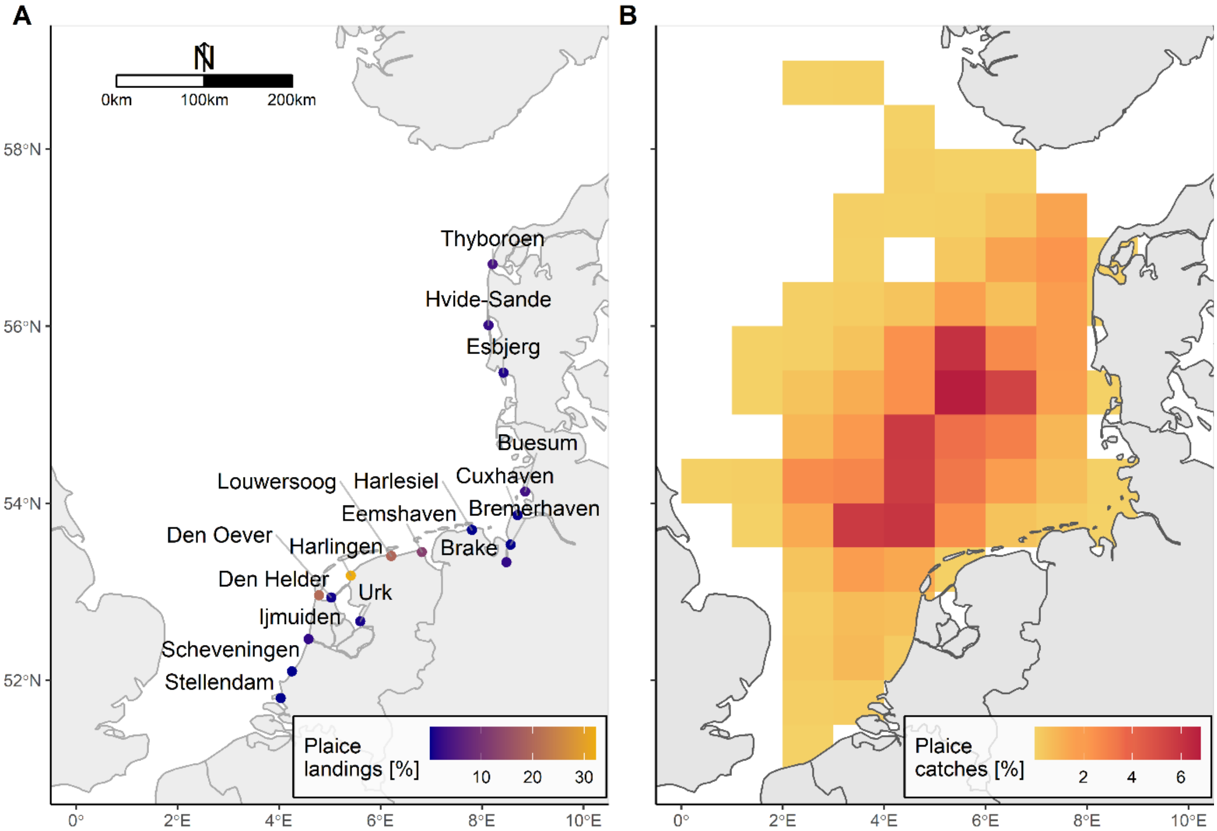


Figure 3.12: Relative proportion of aggregated plaice landings (2009-2019) of the German fleet in North Sea ports (A) and relative proportion of plaice catches (2000-2019) of the German fleet per ICES rectangle (B). Both data sets were cropped to ports and ICES rectangles with at least 0.01 % landings or catches.

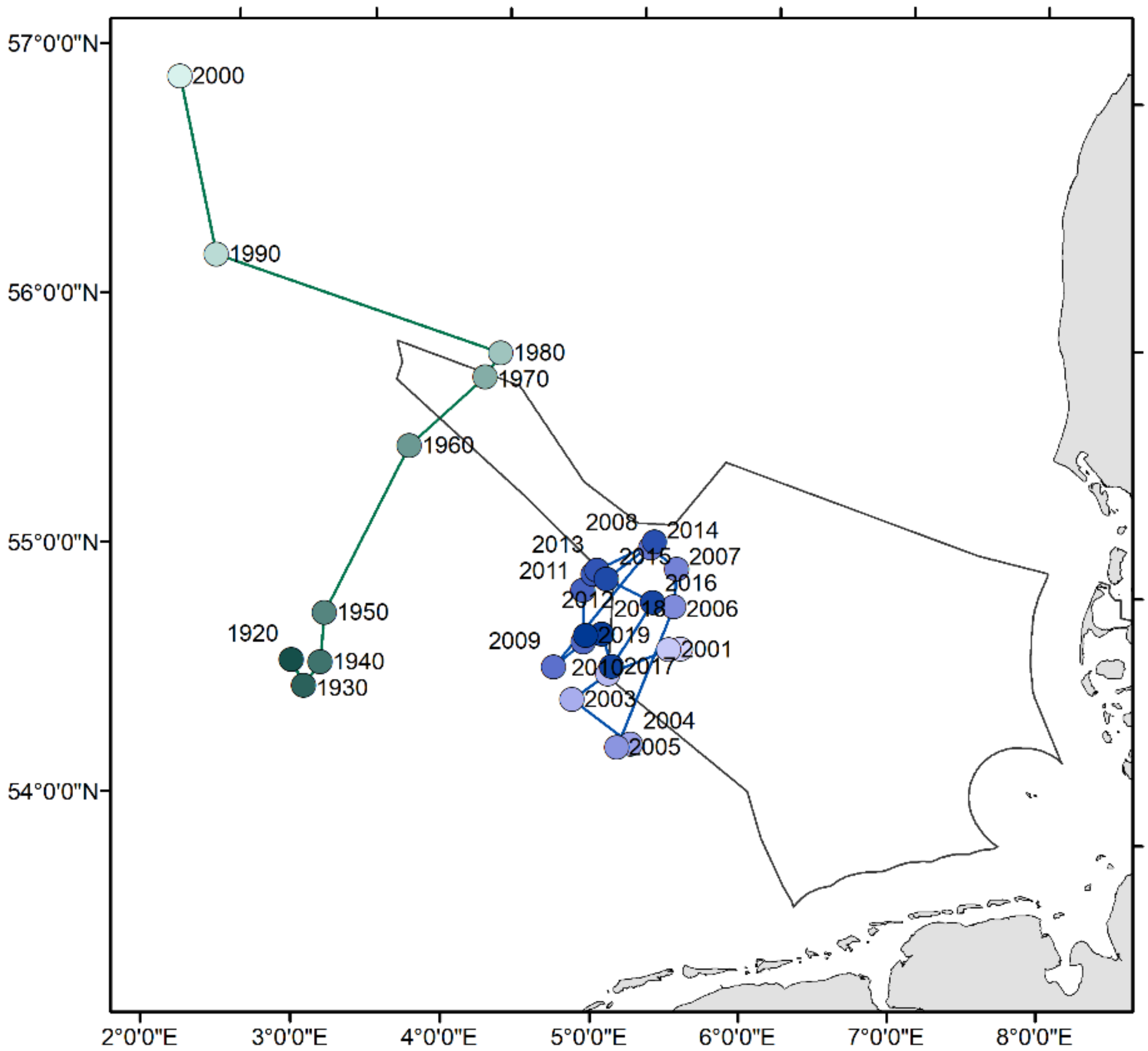


Figure 3.13: Centre of gravity of German plaice landings between 2000 and 2019 (from dark to light blue) and centre of gravity of British trawl plaice landings between the 1920s and the 2000s (from dark to light green) redrawn from Engelhard et al. 2011.

3.D Catch Composition

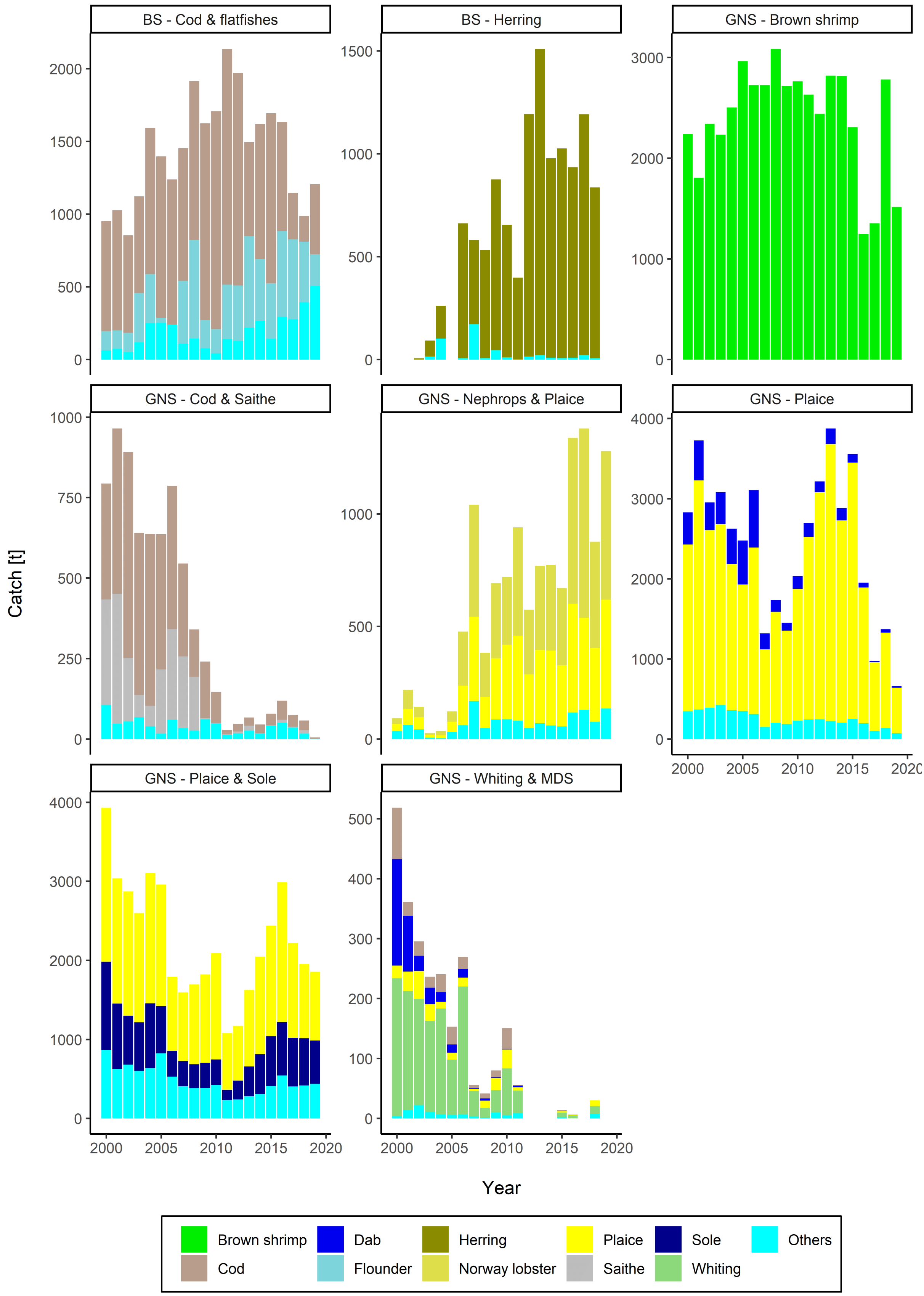


Figure 3.14: Relative catch composition of the seven métiers defined for the plaice related fishery.

3.E Vessel Length

The annual distribution of vessel length (m) for the three plaice dominated métiers are shown in Figure 1. The vessel length for the Nephrops & plaice métier seemed to be relatively constant as the median value settled around 24m for most years. The vessel length of the Plaice & sole métier increased from 2010, hence the distribution shifted to larger vessels (28 m). We observed the same trend for the plaice métier. This might be due to the case that less smaller vessels participated in the fishery or because several large vessels joined the fishery. Figure 2 shows the relative composition of deployed gears (%) for the three métiers. Until 2014, the composition of gears used by German vessels of plaice métiers is mainly composed of beam trawls (TBB), otter bottom trawls (OTB). In 2015 beam trawls became successively replaced by pulse trawls (PULS).

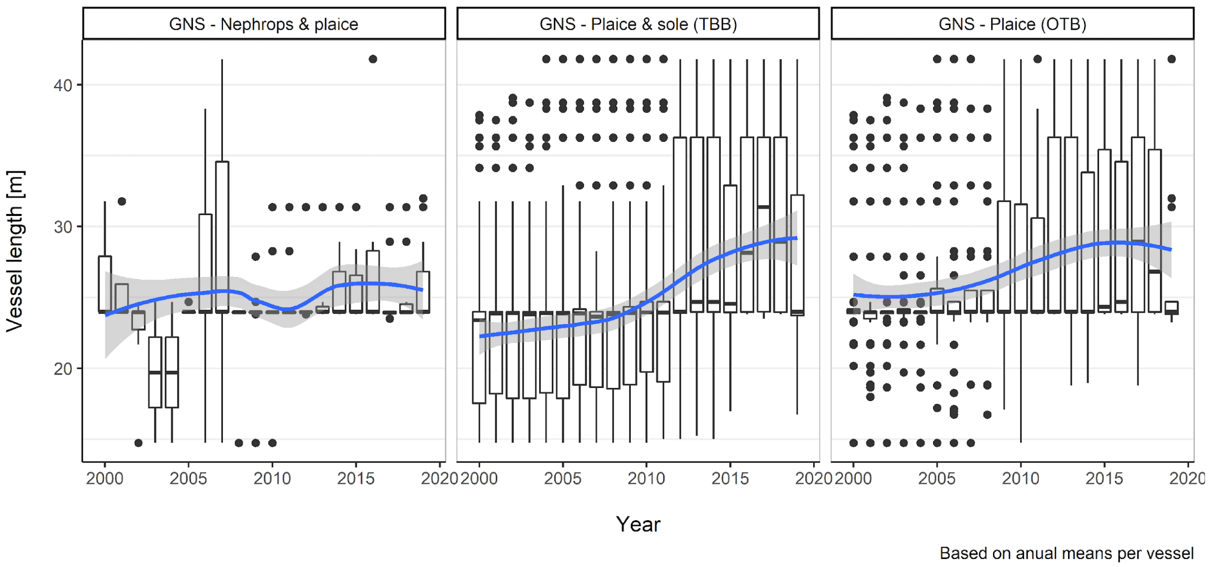


Figure 3.15: The boxplot represents the distribution of annual lengths of vessels participating in plaice related fishing activities. The blue line represents a smoother function using a general additive model (GAM).

3.F Oil Price

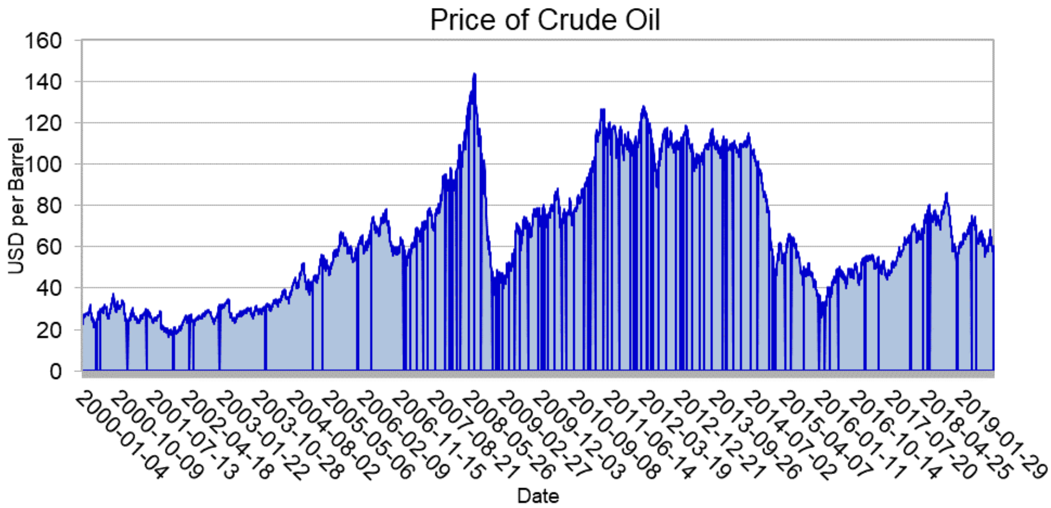


Figure 3.16: Daily oil price. Source: The World Bank 2020. (https://data.worldbank.org/indicator/EP.PMP.DESL.CD. ID: EP.PMP.SGAS.CD. License: CC BY-4.0)

Chapter 4

Interaction Effects in Fisheries

Abstract: Even though unintended catch, or bycatch, has been recognized as an important problem for sustainable management, it is not included in many economic models of fisheries. In this paper, I seek to answer the question, if omitting bycatch in such models causes significantly different results. To this end, a multi-species coupled ecosystem economy model is extended to include bycatch in harvesting. The resulting equilibria and dynamics of the model are solved analytically. This allows demonstration of the effects of bycatch not only on the ecosystem, which are comparatively well researched, but also on the economic actors harvesting and consuming fish stocks. The main results, besides replicating the finding that bycatch can increase harvesting mortality, are that simultaneous harvest properties may have no effects on stocks and that the harvesting economy may change dramatically if discards are banned. Therefore, bycatch should indeed be taken into account in the economic modelling of fisheries. Furthermore, understanding the interrelation of bycatch and market forces is essential in designing overarching policy where economic effects, such as changing employment, need to be considered while also ensuring sustainable use of the ecosystem.

Keywords: Multi-Species Fisheries, Dynamic Modelling, Market Incentives, Compliance, Ecological-economic systems

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This chapter is consists of the paper "Modelling Interactions of Fish, Fishers and Consumers: Should Bycatch be Taken into Account?" published in Hydrobiologia by Blanz (2019)

4.1 Introduction

The behaviour of human actors is one of the key challenges in sustainable management of ecosystems and especially fisheries management. One of the goals of environmental economics is to develop a better understanding of the interrelation of human behaviour and ecosystem dynamics. With regard to fisheries this concerns the behaviour of fishers, the suppliers on the markets for fish products, but also consumers, the demand side on these markets. These issues are further complicated by imperfect selectivity in harvesting in the fishing process. This unintended catch of other species besides the target species is called bycatch in the following. To better understand the direct and indirect effects that bycatch has on harvesting rates, economic variables and long run stock levels a model is developed which includes bycatch in harvesting in addition to interaction between species within the ecosystem and consumer demand.

Imperfect selectivity is investigated in e.g. Skonhoft et al. (2012) and Nieminen et al. (2012). In the literature catch of fish which are too young or otherwise too small to be economically attractive are also often considered as bycatch (Davies et al., 2009). These are not included in the following analysis, focussing instead only on caught species of fish. While the choice of the fishing vessel, gear and the choice of the fishing area can influence the species composition of the catch, perfect selectivity is seldom possible in practice. Additionally, achieving higher selectivity is generally assumed to be costly (Abbott and Wilen, 2009; Singh and Weninger, 2009). However, the fisher may not always be aiming to minimize the catch of other species as these may also have market value. This is especially the case for multi-species fishery, where the simultaneous catch of multiple species is the goal and not something to be avoided. In the model presented in this paper all catch, targeted and bycatch, is landed and sold on the market. This is enforced by the goods market clearing condition, i.e. there is no waste, everything that is produced has to be consumed.

The effect that bycatch has on the ecosystem is difficult to estimate. This is due to the unreliability of self reported data by fishers and the stochastic nature of bycatch. A number of studies have been performed in order to estimate bycatch amounts (Davies et al., 2009; Hall et al., 2000; Lewison et al., 2004; Harrington et al., 2005). Davies et al. (2009) estimate that on a global scale 40% of total fishing mortality is due to bycatch, while stating that the true value is likely to be even larger. The mortality of the fish caught as bycatch depends on a number of factors, such as air exposure and temperature changes (Davis, 2002). In any case, it is not small enough to be safely ignored.

A problem that arises in conjunction with bycatch is that fishers may have incentives to discard part of their catch at sea. This may either be in order to avoid exhausting quotas or other management measures enforced at port or to continue fishing, increasing the average value of the fish in the hold. While the implications of discarding by fishers have been studied and shown to be important (e.g. Boyce (1996); Herrera (2005)), such behaviour is omitted in the model used for this paper in order to keep the analysis tractable. However, the model results are discussed with the possibility of discarding in mind. One measure to reduce the amount of bycatch and hence the over-harvesting of non-target species is to ban discarding of bycatch harvests, and sufficiently monitoring compliance. Thereby all fishing mortality becomes subject to existing management measures. One example of such a measure being implemented is the recent ban on discards by the European Union (Borges, 2015). In effect the model used in this paper is formulated with the implicit assumption that such a ban on discards is in effect and perfect compliance has been achieved. Hence, the model results show the full economic effects of the additional harvests through bycatch.

The behaviour of fishers and the incentives governing them have been investigated by a number of authors (e.g. Boyce (1996); Singh and Weninger (2009)), demonstrating that it is important to take the harvesting process into account when designing policy measures, if they are to be incentive compatible. Management approaches discussed in the literature include transferable or vessel specific quotas, landing taxes, gear specific taxes and licensing fees. The effect of transferable quotas is investigated in Boyce (1996), where outcomes under management with transferable quotas are compared to the case without any management, for a single period of harvesting. It is found that the optimal solution can only be achieved if both the target and bycatch species are managed using quotas. In a similar setting, Abbott and Wilen (2009) investigate the individual incentives of fishermen using a game theoretic approach, finding that the policy decision maker is quite restricted in their decision making if large amounts of discards are to be avoided. Herrera (2005) makes the point that in a quata system bycatch should not be interpreted as a production externality but rather as a stochastic risk that the fishermen need to take into account. Furthermore, discarding of bycatch by fishermen is expensive to observe for the decision maker, leading to information asymmetry and moral hazards. Herrera analyses the effect of taxes, trip limits and value-based quotas, and finds that taxes welfare dominate both other types of management. The effect of transferable quotas versus fixed quotas is investigated by Holland (2010) with a focus on rare stochastic bycatch events. In this context purchasing additional bycatch quota can be seen as a form of insurance, allowing the fisher to continue operating after a bycatch event occurs. Holland explores the effects that quota markets have on fishers' profits as well as risks compared to fixed quota allocation. Furthermore, he explores how the risks can be reduced with market insurance and pooling approaches, which are reported to be quite common even though they are not always formally agreed upon.

However, the incentives that fishers face are not entirely controlled by policy considerations, but strongly dependent on the prices for fish products on the goods markets. Therefore, if the behaviour of fishers is to be modelled, these markets should also be included. A key result of previous research that includes the consumers is the identification of the significant effect that consumer preferences have on the dynamics and equilibria of the ecosystem (Baumgärtner et al., 2011). The consumer preferences for diversity in consumption of fish, in particular, may cause sequential collapse of ecologically independent species (Quaas and Requate, 2013). This would be unexpected for an observer not aware of the economic actors. These results are a strong argument for ecosystem based management approaches (Möllmann et al., 2014) and for taking human behaviour into account.

To investigate the combined effects of bycatch, fisher behaviour and consumer preferences on fish stocks it is necessary to include bycatch as well as consumer preferences in the model. The coupled ecosystem economy models used in Baumgärtner et al. (2011) and Quaas and Requate (2013) but also in others (e.g. Quaas et al. (2013); Derissen et al. (2011)) include consumer preferences, fishers and ecosystem stocks, but fisheries are simplified in such a way that each target species can be harvested perfectly independently of the other species present. These models have been used successfully to investigate how consumer preferences can cause over-fishing of the targeted species, but not to investigate the effects of bycatch. Hence, in this work, the coupled bio-economic model developed by Quaas and Requate (2013) is extended to include bycatch in harvesting in order to investigate the combined effects of bycatch and human behaviour. This model consists of a multi-species stock based ecosystem module and an economy model in which consumers and harvesting firms determine harvests by maximizing their utility and profits respectively, which in turn depend on the current state of the ecosystem.

To answer the question posed in the title, if bycatch should be considered in economic modelling of fisheries, conditions are determined under which the model results are independent of the amount of bycatch. Furthermore, it is shown that bycatch can significantly increase the fishing mortality, increasing the risk of catastrophic over-fishing, but also may have dramatic effects on the harvesting firms.

The remainder of this paper is structured as follows: First a detailed explanation of the new model, extended from Quaas and Requate (2013) to include bycatch, is given. Following the model description, results are shown for different bycatch intensities, in addition to targeted catch, and keeping the total catch per firm constant. In the final section these results are discussed, followed by concluding remarks as to the importance of the results for fisheries management.

4.2 Model Design

In order to investigate the consequences of interactions in harvesting between species caused by bycatch, these need to be disentangled from interactions between species stemming from ecological properties of the species, or preferences for certain proportions of species in consumption. Only if all of these avenues of interaction between species are included in the model can the direct effects of bycatch be distinguished from those caused by indirect effects from market adjustments. With this aim an existing model from the literature (Quaas and Requate, 2013) which includes interaction between the demand for different species was extended to also include technological interaction in harvesting and ecosystem interaction between species. With these extensions the model was then fully solved, determining the full equations of motion for the coupled system.

In order to accommodate empirical evidence on the limited willingness of consumers to substitute one species for another in consumption (Asche et al., 1997; Barten and Bettendorf, 1989; Fousekis and Revell, 2004), the Dixit-Stiglitz utility function (Dixit and Stiglitz, 1977) is chosen by Quaas and Requate (2013). The parameter σ in that function can be interpreted as the preferences for a diversity in the consumption of fish.

The addition of bycatch does not change the utility function, but it does create a further restriction on the household optimisation problem in addition to the (unchanged) budget constraint. In contrast to the case without bycatch, the ratio in which species are supplied is not necessarily free, but may be restricted by the properties of the harvesting gear. The firm optimisation problem is changed to properly reflect the extra harvests achieved with each gear. The number of firms employing a specific combination of vessel type and gear, a certain métier, depends on the prices and quantities of all species that are caught using that vessel and gear combination. Therefore, market prices are not only related through the demand function, but also through the available harvesting technology. The ecosystem portion of the model is based on Baumgärtner et al. (2011). The fish stocks are represented by a standard multi-species biomass growth model. While ecological interactions between species can be included in the model, the parametrisation used in this paper excludes them.

4.2.1 Ecosystem Properties

The ecosystem contains $\bar{i}$ species, which are modelled using stock variables to measure the current amount of biomass of each species relative to the ecosystem's carrying capacity for each species. Stocks are denoted by x with indexes for species $i \in I$, where I is the set of all species $I = [1, \bar{i}] \cap \mathbb{Z}$. Species are assumed to grow each period due to intrinsic growth g_{it} and are diminished by harvests H_{it}. This change in stocks is modelled by differential equations, determining the dynamics of the model.

$$\dot{x}_{it} = g_{it}(\vec{x}_t) - H_{it} \tag{4.1}$$

The vector of ecosystem stocks $\vec{x}$ completely determines the state of the model. The other variables are modelled as adjusting instantaneously to changed stocks in each period. Their adjustment processes are not resolved within the model. In the following all variables without a time index, are taken to be contemporary.

Intrinsic growth is represented by the logistic growth function $g_i(\vec{x})$, which depends on the entire vector of stocks, due to possible interactions between species, which are measured by the species-specific interaction vectors $\vec{\gamma}_i$. It is possible for intrinsic growth to become negative, if stocks fall below minimum viable population levels.

$$g_i(\vec{x}) = r_i(x_i - \underline{x}_i)\left(1 - \frac{\vec{\gamma}_i\vec{x}}{\kappa_i}\right) \tag{4.2}$$

4.2.2 Harvesting Properties

Per period harvests of each species are the result of choices made by the economic actors within the model. As such harvesting pressure is not an exogenously set parameter, but is endogenously determined depending on the state of the ecosystem, available harvesting gear and vessel types and consumer preferences.

The component of the model describing the harvests includes $\bar{k}$ métiers. In the context of this model, a métier encompasses all that is necessary for the fisher to harvest which is not dependent on the effort. I.e. all upfront investments that are necessary to start operating. This includes fishing gear, vessel, license costs and similar expenditures. Each firm is assumed to employ a single vessel with a single gear type. While individual firms may not change their métier, the economy wide fleet size for each métier is dynamic. The change of gear in use occurs through market entry and exit of firms performing different métiers. Métiers are indexed by $k \in K$, where K is the set of all métiers $K = [1, \bar{k}] \cap \mathbb{Z}$. Each has a certain target species, but may also catch other species present, as bycatch.

In the case without bycatch it is assumed that the market supports at most one métier per targeted species.

Assumption 1. $\bar{k} = \bar{i}$

To arrive at this assumption it can be imagined that initially there are more métiers practised. However, for each species one gear and vessel combination will be the most efficient at harvesting that species. Implying that firms practising these most efficient métiers will be able to sell at lower prices, compared to those practising less efficient métiers, driving them out of the market. As the different species are imperfect substitutes in consumption, one métier per species will be left.

Total harvest H_i of species i is calculated as the number of firms practising métier k (n_k) multiplied by the per firm harvest of species i practising métier k (h_{ik}) summed over all métiers.

$$H_i = \sum_{k=1}^{\bar{k}} n_k h_{ik}(e_k, x_i) \tag{4.3}$$

The per firm harvest is described by a generalised Gordon-Schaefer production function (Clark, 1990). It is a function of the effort employed by firms practising the métier e_k and the stock being harvested x_i. Harvesting effort e_k experiences diminishing returns, governeed by the returns to effort ϵ. However, harvest is not only determined per species as in Quaas and Requate (2013), but also per métier. The fisher may choose the métier k, but she has no direct control of species of fish she catches. Hence, the total amount harvested of a specific species i (H_i) depends on the effort e_k made practising all métiers k capable of catching that species ($k \in \{K|\nu_{ik} > 0\}$). The gear effect is governed by the gear matrix ν. The elements of which (ν_{ik}) specify the catchability for each of species i by métier k.

$$h_{ik}(e_k, x_i) = \nu_{ik} e_k^{\epsilon} \chi(x_i) \tag{4.4}$$

The métiers and species are indexed in such a way that the l^{th} métier has the l^{th} species as its target. It is assumed that each métier is the most efficient for its target. This implies that in the l^{th} row ν written as $\vec{\nu}_{i=l}$ the largest element will be at the l^{th} position.

Assumption 2. $\arg\ \max_k \vec{\nu}_{i=l} = l \ : \ k \in K$

In the case of perfectly targeted harvesting, i.e. no bycatch, ν is a diagonal matrix and Assumption 2 is trivially satisfied. The diagonal elements of ν specify the métier efficiency for the harvest of each species. Each species is harvested by a single métier and activity in that métier does not yield harvests for other species. More formally $h_{ik} > 0$ for $k = i$ and $h_{ik} = 0$ otherwise. Conversely, in the case with bycatch, modelled in this paper, any métier may catch any species i.e. $h_{ik} \geq 0 \ \ \forall k \in K, i \in I$ subject to Assumption 2. In both cases it is assumed that no useless métiers exist. A useless métier would be less efficient than an existing one at harvesting the same species in the same ratio or would yield no harvest at all given the current stock levels. This implies that the product of the stock dependent harvesting efficiency, described below, and the gear efficiency matrix has full rank.

Assumption 3. $\quad \text{rank}(\chi\nu) = \bar{k}$

Species abundance influences the harvest returns per effort through the harvestability function $\chi_i(x_i)$. The harvestability function captures changes in harvest yield due to changing stocks. A less abundant species is more difficult to catch compared to one with high stock levels.

$$\chi_i(x_i) = x_i^{\chi_i} \tag{4.5}$$

In the following $\chi_i(x_i)$ will be abbreviated as χ_i. A further shorthand χ (no index) is used in some of the derivations in the appendix and in Assumption 3. It specifies a square matrix containing the χ_i along the diagonal and zeros off the diagonal.

The effort of each firm is determined under the assumption of perfect markets for harvested goods and labour. Each firm takes stock levels x_i, prices p_i and wages ω as fixed and maximizes individual short term profits. Fixed costs associated with harvesting ϕ_k are determined by the métier practised. The representative firm per métier then solves the following profit maximizing problem in order to determine their effort level e_k.

$$\max_{e_k} \sum_{i=1}^{\bar{i}} h_{ik}(e_k, x_i)p_i - \omega e_k - \phi_k \tag{4.6}$$

Due to the assumed perfect markets, firms' profits will be zero. This in conjunction with profit maximization results in the zero-profit optimal métier-specific effort level e_k^*, the derivation of which can be found in Appendix 4.A.

$$e_k^* = \frac{\phi_k}{\omega} \frac{\epsilon}{1-\epsilon} \tag{4.7}$$

The optimal effort level differs for individual métiers as each métier is assumed to have specific positive fixed costs ϕ_k. Substituting e_k^* into the harvesting production function (4.4) yields the per firm métier specific equilibrium harvest.

$$h_{ik}(x_i) = \nu_{ik} e_k^{*\epsilon} \chi(x_i) \tag{4.8}$$

4.2.3 Household Properties

Households are modelled by a single representative household. The household's preferences over consumption of fish Q and a numeraire commodity y are formalized in the household utility function.

$$U(Q, y) = \begin{cases} y + \alpha \dfrac{\eta}{\eta - 1} Q^{\frac{\eta-1}{\eta}} & \text{for } \eta \neq 1 \\ y + \alpha \ln Q & \text{for } \eta = 1 \end{cases} \tag{4.9}$$

The parameter $\eta > 0$ describes the constant demand elasticity of fish, while $\alpha \geq 0$ measures the relative importance of fish consumption in overall consumption. The household's preferences over the available species of fish are modelled using a Dixit-Stiglitz utility function (Dixit and Stiglitz, 1977).

$$Q = Q(\vec{q}) = \left(\sum_{i=1}^{\bar{i}} q_i^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \tag{4.10}$$

The elasticity of substituting between consumption levels of different species q_i is measured by $\sigma > 0$. Perfect substitution would be achieved for $\sigma \to \infty$, while lower values indicate limited substitutability of fish species in consumption.

The representative household maximizes (4.9), choosing y and the q_i subject to the household budget constraint:

$$\omega = y + \sum_{i=1}^{\bar{i}} p_i q_i \tag{4.11}$$

In each period the household receives income from providing labour to the fisheries and manufacturing sectors. All household income ω is spent either on fish, according to the amounts consumed q_i and prices p_i, or on a manufactured good y the price of which has been normalised to one. To keep the analysis tractable, no saving or other capital accumulation is possible in the model. The manufactured good is taken to represent all other consumption, besides fish. The wage rate ω is determined by the marginal productivity of labour. This is defined by the production function of the numeraire commodity, which is shown in the following section.

As species are not supplied independently, due to the introduction of bycatch in harvesting, the goods market clearing condition implies an additional restriction on household demand, not present in Quaas and Requate (2013).

$$q_i = H_i = \sum_{k=1}^{\bar{k}} n_k h_{ik}(x_i) \tag{4.12}$$

Furthermore, basic realism forbids contemplating negative firms. This is formalized by the non-negativity conditions on each of the $\bar{k}$ numbers of firms variables n_k.

$$n_k \geq 0 \tag{4.13}$$

As it is not known *ex ante* if this condition will be binding or not, it can not be simplified to an equality.

In order to solve the household optimisation problem under these conditions the Kuhn-Tucker conditions are used (Kuhn, 2014). To simplify the analysis the goods market clearing condition (4.12) is substituted into the sub-utility for fish (4.10) and the budget restriction is reformulated.

$$\tilde{Q} = \tilde{Q}(\vec{n}) = \left(\sum_{i=1}^{\bar{i}} \Bigg(\underbrace{\sum_{k=1}^{\bar{k}} n_k h_{ik}(x_i)}_{q_i} \Bigg)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \tag{4.14}$$

$$\begin{aligned} c_k &= e_k^* \omega + \phi_k \\ &= \phi_k \left(1 + \frac{\epsilon}{1-\epsilon}\right) \end{aligned} \tag{4.15}$$

Hereby the c_k represents the operating costs of each firm of type k. The firm costs do not depend on any variables as it is assumed that firms operate at the zero-profit profit-maximizing level (4.7). Given that firms operate at this equilibrium level, the sum of costs multiplied with the number of firms must equal the sum of prices multiplied by consumed amounts of species.

$$\sum_{k=1}^{\bar{k}} c_k n_k = \sum_{i=1}^{\bar{i}} p_i q_i \tag{4.16}$$

This is substituted into (4.11) to yield the reformulated budget constraint.

$$y = \omega - \sum_{k=1}^{\bar{k}} c_k n_k \tag{4.17}$$

The representative household now chooses the type and number of bundles of fish in order to maximize utility. Bundles consist of certain amounts of each harvestable species. The composition of the bundles is defined by equilibrium output of a single firm of each type $h_k(\vec{x})$.

$$h_k(\vec{x}) = \begin{pmatrix} h_{1k}(x_1) \\ \vdots \\ h_{\bar{i}k}(x_{\bar{i}}) \end{pmatrix} \tag{4.18}$$

The Lagrangian of the household optimisation problem then is:

$$\mathcal{L}(\vec{n}) = \omega - \sum_{k=1}^{\bar{k}} c_k n_k + \alpha \frac{\eta}{\eta - 1} \left(\sum_{i=1}^{\bar{i}} \left(\sum_{k=1}^{\bar{k}} n_k h_{ik}(x_i) \right)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}} - \sum_{k=1}^{\bar{k}} \lambda_k(-n_k) \tag{4.19}$$

As $\ln(Q)$ is the continuous extension of $\frac{\eta}{\eta-1} Q^{\frac{\eta-1}{\eta}}$ the first order conditions derived using the above equation also extend to the case $\eta = 1$. The first order conditions are:

$$\frac{\mathrm{d}\mathcal{L}(\vec{n})}{\mathrm{d}n_k} = 0 \tag{4.20}$$

$$\lambda_k \geq 0 \tag{4.21}$$

$$-n_k \leq 0 \tag{4.22}$$

$$-\lambda_k n_k = 0 \tag{4.23}$$

To determine the solution to the household optimisation problem, it is split into cases depending on the number of métiers practised. The cases considered are:

1. All métiers are practised

2. Only one métier is practised

3. Not all métiers are practised, but more than one

In order to keep the analysis simple, for the remainder of this paper only two species and métiers are considered. This removes the third case from consideration.

Assumption 4. $\bar{k} = \bar{i} = 2$

Case 1: All Métiers Practised

For the case where none of the non–negativity conditions are binding the restriction can simply be omitted and the solution to the household optimisation problem can be found using a basic Lagrangian approach. The derivation of the household demand function for individual species of fish can be found in Appendix 4.B.1. This function relates the amount of each species demanded (and consumed) to the prices of all available species.

$$q_i = \alpha^\eta p_i^{-\sigma} \left(\sum_{i'=1}^{\bar{i}} p_{i'}^{1-\sigma} \right)^{\frac{\sigma-\eta}{1-\sigma}} \tag{4.24}$$

The household demand function in this case is unaffected by the bycatch introduced into harvesting, and is therefore equal to the one found in Quaas and Requate (2013). The derivation of prices and number of active firms however is somewhat more complicated, due to the additional interrelation of prices and number of firms on the supply side.

The number of active firms in this case is found by solving the goods market clearing conditions for each of the $\bar{i}$ species simultaneously. The number of firms per métier is then determined by solving the corresponding linear system of equations.

$$\vec{n} = {}^{n}A^{-1} \; {}^{n}\vec{b} \tag{4.25}$$

The components of the linear system of equations are given by:

$$
\begin{aligned}
{}^{n}A &= \nu \;\; \mathrm{diag}(e^{\vec{*\epsilon}}) \\
{}^{n}\vec{b} &= \chi^{-1}(\vec{x}) \; \vec{q}(\vec{p}) \\
{}^{n}b_i &= \chi^{-1}(x_i) \; q_i(\vec{p})
\end{aligned}
$$

The derivation of the above can be found in Appendix 4.B.3.

For the case with only two species and métiers, i.e. Assumption 4 holds, the solution to the linear system of equations determining the number of firms practising each métier can be written as follows:

$$n_1(q(\vec{p})) = e_1^{*-\epsilon}\chi_1^{-1}\chi_2^{-1}(\nu_{11}\nu_{22} - \nu_{12}\nu_{21})^{-1}(\nu_{22}\chi_2 q_1(\vec{p}) - \nu_{12}\chi_1 q_2(\vec{p})) \tag{4.26}$$

$$n_2(q(\vec{p})) = e_2^{*-\epsilon}\chi_1^{-1}\chi_2^{-1}(\nu_{11}\nu_{22} - \nu_{12}\nu_{21})^{-1}(\nu_{11}\chi_1 q_2(\vec{p}) - \nu_{21}\chi_2 q_1(\vec{p})) \tag{4.27}$$

In the case of all métiers being practised, prices will equal average production costs of the harvesting firms. Prices are determined by solving the zero profit conditions of all $\bar{k}$ métiers simultaneously. This yields prices as the solution of a linear system of equations.

$$\vec{p} = {}^{p}A^{-1}\,{}^{p}\vec{b} \tag{4.28}$$

The components of which are defined as follows:

$$\begin{aligned}
{}^{p}A &= \nu^{\intercal}\chi \\
{}^{p}\vec{b} &= \begin{pmatrix} {}^{p}b_1 \\ \vdots \\ {}^{p}b_{\bar{k}} \end{pmatrix} \\
{}^{p}b_k &= \phi_k\left(1 + \frac{\epsilon}{1-\epsilon}\right)\left(\frac{\phi_k}{\omega}\frac{\epsilon}{1-\epsilon}\right)^{-\epsilon}
\end{aligned}$$

The derivation of the individual components can be found in Appendix 4.B.2. Deriving prices in this way requires Assumption 1.

In the case with only two species and two métiers is considered, i.e. Assumption 4 holds, the solution to the above linear system of equations can be written as follows:

$$p_1 = (\chi_1)^{-1}(\nu_{11}\nu_{22} - \nu_{12}\nu_{21})^{-1}(\nu_{22}\,{}^{p}b_1 - \nu_{21}\,{}^{p}b_2) \tag{4.29}$$

$$p_2 = (\chi_2)^{-1}(\nu_{11}\nu_{22} - \nu_{12}\nu_{21})^{-1}(\nu_{11}\,{}^{p}b_2 - \nu_{12}\,{}^{p}b_1) \tag{4.30}$$

Case 2: Only One Métier Practised

With only one métier practised the household optimisation problem is simplified from the one with $\bar{k}$ choice variables to only one. This is achieved by using the fact that the number of active firms for all other métiers is zero. The demand for the bundle of harvested goods produced by the single métier is given by Equation (4.31), the derivation of which can be found in Appendix 4.B.4.

$$n_k = c_k^{-\eta} \alpha^\eta \left(\sum_{i=1}^{\bar{i}} h_{ik}(x_i)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{(\eta-1)\sigma}{\sigma-1}} \tag{4.31}$$

The demand for individual species follows from the goods market clearing condition (4.12), where n_k is replaced by the above demand function and $h_{ik}(x_i)$ is given by (4.8).

$$\begin{aligned} q_i &= n_k h_{ik}(x_i) \\ &= \alpha^\eta c_k^{-\eta} h_{ik}(x_i) \left(\sum_{i=1}^{\bar{i}} h_{ik}(x_i)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{(\eta-1)\sigma}{\sigma-1}} \end{aligned} \tag{4.32}$$

Prices can then be determined using the inverse demand function, which is obtained during the derivation of the demand function for Case 1 in Appendix 4.B.1.

$$p_i = \alpha q_i^{-\frac{1}{\sigma}} Q^{\frac{\eta-1}{\eta} - \frac{\sigma-1}{\sigma}} \tag{4.33}$$

Switching Between Cases

The conditions for switching between these two cases are derived from the first order conditions of the household optimisation problem. Per Equation (4.23), whenever the number of active firms for a specific métier k becomes zero the corresponding slip parameter λ_k becomes greater than zero. Given Assumption 4, it can be assumed without further loss of generality that Métier 1 is the one not practised, while Métier 2 is practised. More formally $n_1 = 0$ and hence $\lambda_1 > 0$ while $n_2 > 0$ and $\lambda_2 = 0$. Substituting this into (4.20) yields the condition for the number of firms practising métier 1 to be zero.

$$0 > \sum_{i=1}^{\bar{i}} (\chi_i \nu_{i2})^{\frac{\sigma-1}{\sigma}} \left(\frac{\nu_{i1}}{\nu_{i2}} - 1 \right) \tag{4.34}$$

The derivation of (4.34) can be found in Appendix 4.B.5.

Given Assumptions 1, 2 and 3, in a parametrisation without bycatch, all métiers would be practised in order to maximize welfare. This can be seen from (4.34) as follows: In the case without bycatch the elements of ν off the diagonal ($\nu_{ik} \quad i \neq k$) would be zero, causing at least one of the factors in each term of the sum to become zero and hence the entire sum to be zero, this would violate the condition for inactivity of a single métier. If parametrised in such a way, the model replicates those described in Quaas et al. (2013) and Quaas and Requate (2013).

An exception to the above is the extinction of a species. In this case, without bycatch, the métier targeting the extinct species would yield no harvest at all, violating Assumption 3. To continue iteration of the model in this case, it is reparametrised to exclude the extinct species and the useless métier, ensuring that Assumption 3 is satisfied once more. This method is employed after the first extinction event shown in Figure 4.1.

Labour Market and the Numeraire Commodity

The representative household supplies an amount of labour normalised to unity. This labour can either be employed in the harvesting sector, as effort e, or in the manufacture of the numeraire commodity y. The latter is produced with labour as its sole input and constant labour productivity equal to the wage rate ω. As a perfect labour market is assumed, the amount of labour employed in each of the sectors will balance such that the marginal productivity of labour is equal in both.

Given the effort levels determined for the harvesting sector, and the costs associated with the métiers, the production of the numeraire commodity is determined by the labour productivity (equal to the wage rate ω) multiplied by the amount of labour available to the manufacturing sector minus economy wide fixed costs of harvesting, closing the model.

$$y = \omega \left(1 - \sum_{k=1}^{\bar{k}} n_k e_k^* \right) - \sum_{k=1}^{\bar{k}} n_k \phi_k \tag{4.35}$$

Parametrisation

The standard parametrisation of the model used in this section is shown in Table 4.1. The model includes two species which are harvested, without bycatch, by two métiers. Bycatch is added later in the analysis and the results compared to the standard parametrisation. The first species has a higher intrinsic growth rate and is easier to harvest compared to the second species. The species are not prone to intrinsic stock collapse and do not compete for resources, i.e. the species grow independently of each other. Métier 1 is associated with higher fixed costs compared to Métier 2. Household preferences allow for some substitution between fish species. A low weight of fish consumption in utility was chosen for the standard parametrisation to ensure that the stocks are not immediately depleted.

Species' intrinsic growth rates are chosen for demonstration purposes but are broadly in line with the motivation. Interspecies competition and minimum population thresholds are parametrised out of the model in order to not confuse results. The carrying capacities of both species have been normalised to one. The ecosystem parametrisation impacts the model results through the relative differences in stock growth. In the chosen parametrisation the only difference in growth comes from the intrinsic growth rates. As the household would ideally consume equal amounts of each species, the price for the more productive species will be lower.

Positive fixed costs ϕ ensure positive harvesting effort in the firm optimisation problem. The wage and hence the price of the numeraire commodity are normalised to unity. The métier specific harvesting efficiencies are chosen to balance the intrinsic growth rates of the species. In the standard parametrisation bycatch harvesting efficiencies are set to zero.

The choice of $\eta = 1$ and $\sigma = 2$ follows Quaas and Requate (2013). These values ensure limited substitutability between the consumption of fish species i.e. a preference to substitute reduced consumption of one species by another fish species instead of the numeraire commodity. Values of $\sigma > 1$ ensure that the marginal utility of species i remains positive even if the consumption of another species becomes zero. Furthermore, $\eta = 1$ ensures that if only one métier is practised, the number of firms practising that métier is independent of the bycatch intensity. Thereby the direct effect of bycatch can be observed in results without adjustment in the number of firms.

The real world motivation for the parametrisation are the coastal fisheries in the German Bight. This fishery mainly targets two species, plaice and sole, where one species, plaice, is typically larger than the other, sole. This implies that plaice can be caught with near perfect selectivity as a mesh size aimed at catching plaice will allow sole to pass through. The same cannot be said when targeting sole. In that case a smaller mesh size is necessary, catching both species. This bycatch structure implies that the top right

Table 4.1: Standard parameter values used in this paper. This parametrisation does not include bycatch as the elements of ν off the diagonal are zero. Assumptions 1, 2, 3 and 4 are all satisfied by this parametrisation.

Symbol	**Description**	**Value**
	Ecosystem Parameters	
$\bar{i}$	number of species	2
$\bar{k}$	number of harvesting métiers	2
r	species-specific intrinsic growth rates	$(1.2, 0.5)^\intercal$
κ	species-specific carrying capacity	$(1, 1)^\intercal$
$\underline{x}$	species-specific minimum viable population	$(0, 0)^\intercal$
γ	interspecies resource competition matrix	$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$
	Harvesting Firms Parameters	
ω	wage rate	1
ϵ	returns to effort	0.5
ν	métier- and species-specific harvesting efficiency	$\begin{pmatrix} 1 & 0 \\ 0 & 0.4 \end{pmatrix}$
χ	species-specific stock dependent harvesting efficiency	$(0.33, 0.33)^\intercal$
ϕ	métier-specific fixed costs	$(0.8, 0.25)^\intercal$
	Household Parameters	
α	importance of fish consumption in household utility	0.4
η	substitution elasticity of fish consumption	1
σ	substitution elasticity between fish species	2

entry of the gear matrix ν_{12} (the catch of Species 1 by Métier 2) is positive. The effects of this are is discussed in the following sections.

Condition for No Effect of Bycatch

An interesting analytical result can be derived from the model equations. As prices are directly linked with harvests and hence stocks, if prices do not change in response to a change in harvesting efficiency the other variables will also remain constant. The condition for this (4.36), called "the condition for no effect of bycatch" below, is obtained by setting the derivatives of one of the prices to ν_{1k} equal to the derivative of ν_{2k}. If there is to be no effect, the derivatives of the two parameters being simultaneously changed need to cancel each other out. This is shown in Appendix 4.C.

$$\frac{\phi_1}{\phi_2} = \left(\frac{\nu_{11} + \nu_{21}}{\nu_{12} + \nu_{22}}\right)^{\frac{1}{1-\epsilon}} \tag{4.36}$$

This condition drives the results showing that it is possible for the direct and indirect effects of bycatch to perfectly balance each other out.

Implementation

Further qualitative results are obtained from the model by observing the dynamics. Results regarding the direct and indirect effects of bycatch are shown by iterating the model equations over time and investigating the global equilibria also known as steady states of the model. To this end the analytically derived equations of the model are implemented in the R programming language (R Core Team, 2017). Steady states are then determined using the R package rootSolve (Soetaert and Herman, 2009, Chapter 7). To determine the effect that additional bycatch has on the model results, the interior equilibria of the model are investigated. This equilibrium is stable with both stocks present. The model contains a number of other stable equilibria, most notably the asymmetric stable equilibria, where one species survives while the other is extinct, and of course total extinction.

4.3 Results

To fully determine the effect that bycatch has not only on ecosystem stocks, but also on economic variables, the model introduced above incorporates economic activities as well as ecosystem properties in a fully coupled manner. Thereby model results show the indirect effects of bycatch in addition to the direct changes in harvesting efficiency. These indirect effects are the results of the fisheries market adjusting to changes in harvesting costs, resulting from changed harvesting efficiencies (the direct effects). These adjustment processes are revealed in the responses of prices and number of firms practising specific métiers to changing harvesting efficiencies. The economic adjustment processes are assumed to be instantaneous compared to the more slowly adjusting ecosystem stocks. Hence the short- and long-term results of different levels of bycatch may differ significantly until a global equilibrium, also known as a steady state, of the model is reached.

The key result derived from the model is that the total effect of bycatch may strongly differ from the direct effect. This is especially the case when more than one period is considered, as the adjustment processes causing the indirect effects not only depend on parameters but also on (changing) stock levels. Hence, the deviation between predictions may compound over time. An example of how the indirect effects alter outcomes and the difference between estimates of the impact of bycatch is shown in Figure 4.1 for ecosystem stocks and selected economic variables. For these model runs consumer demand for fish was increased to better illustrate the result ($\alpha = 0.8$). The leftmost column shows how the ecosystem stocks and economic variables adjust in response to each other under the assumption of perfect selectivity. The only interactions between the harvests of the two species in this case stem from consumer preferences. For the centre left column bycatch is added to Métier 2 ($\nu_{12} = 0.24$), while the number of harvesters practising each métier is fixed to the levels derived without bycatch. This shows the direct results of bycatch on stocks over time, omitting any economic adjustment. Prices can not be determined in this context, as markets are not allowed to adjust such that demand and supply equal. As is to be expected, the increased harvesting efficiency for Species 1 causes its stocks to decline, while harvests of the other species, not impacted by bycatch, remain constant. For the center right column some economic behaviour is enabled. There, harvesters' effort level is endogenously determined, maximizing profits given the fixed prices taken from the no bycatch case. Even this limited economic behaviour significantly changes

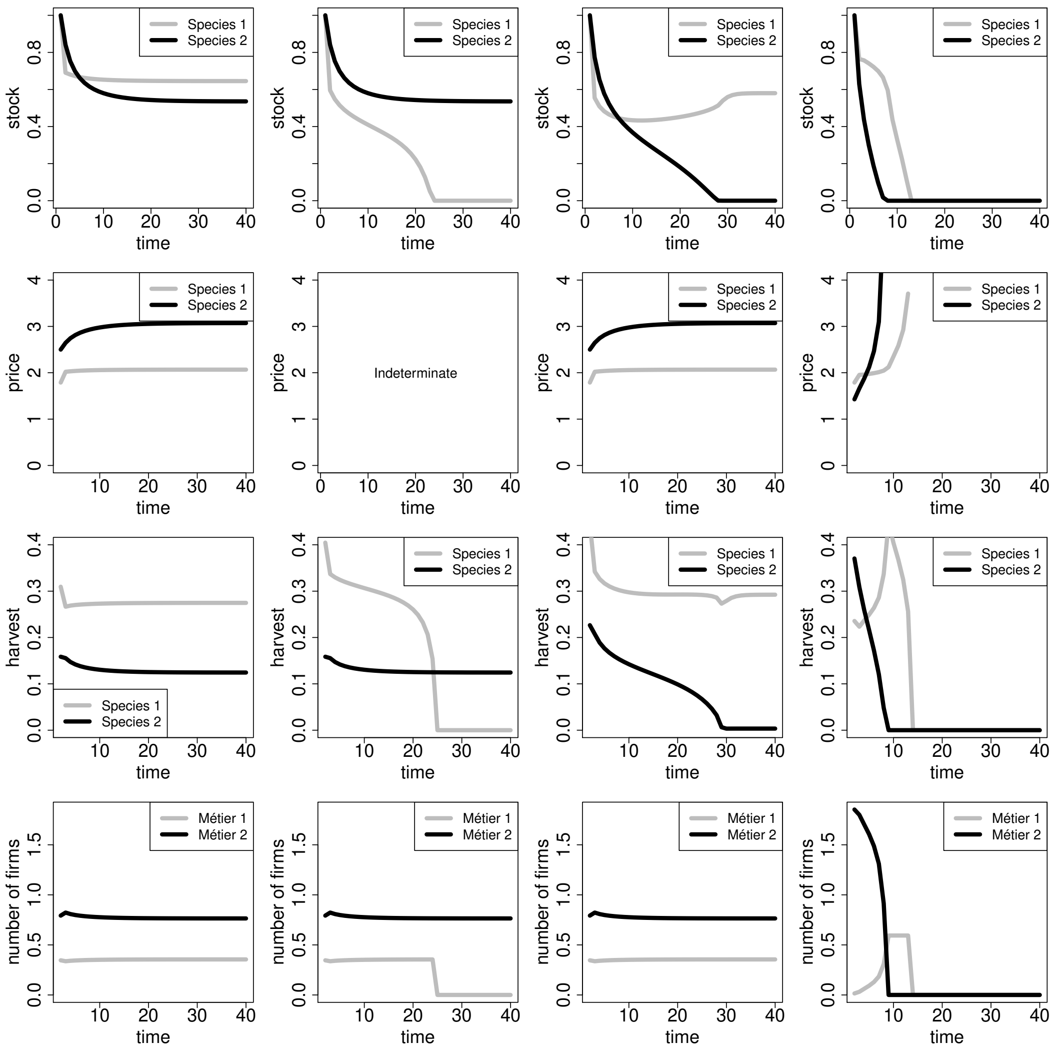

Figure 4.1: Simulation results without (left column) and with bycatch ($\nu_{12} = 0.24$ other columns) with different economic adjustment behaviours enabled. Left column: Full model interactions, no bycatch. Center Left Column: Number of firms fixed to no bycatch levels, no endogenous behaviour by economic actors. Prices can not be determined for this setting, as markets are not allowed to function. Center Right Column: Number of firms and prices fixed to no bycatch levels, endogenous effort choice by harvesters. Right Column: Full model interactions. For all columns the importance of fish consumption in household utility has been increased to make the results more visible ($\alpha = 0.8$). All other parameters as in Table 4.1.

results compared to the previous simulations. Finally, in the rightmost column economic variables are fully endogenous. The market for harvested products adjusts to the higher overall harvesting efficiency of Métier 2. The immediate response is that a significantly larger number of firms choose to practice this now more attractive métier compared to the no bycatch scenario. As the total amount of labour available to the fishing sector is limited, this causes a corresponding drop in the number of firms practising the other métier. This simultaneous drop in the use of Métier 1 more than compensates for the increase in harvests of Species 1 through bycatch as total harvests are lower than in the no bycatch case on the far left. The continuing adjustments over time are a response to changing ecosystem stocks. Changed stocks impact the market as they make up part of the harvesting costs. This can be observed in the strongly increasing prices, as stocks are depleted. However, the increase in prices is not sufficient to deter consumers, leading to the complete depletion of both species in this scenario. This extreme outcome is partly caused by the high relative importance of fish consumption in utility for these illustrations ($\alpha = 0.8$). For lower values of that parameters the increase in prices is sufficient for consumers to reduce consumption, reducing harvests. In those cases interior equilibria exist.

A second result relates to the interior equilibria or steady states of the model, depending on various bycatch intensities. In this context decreases in the target harvesting efficiency with increasing bycatch are also considered. The stable interior equilibria for varying levels of the bycatch harvesting efficiency of Métier 2, i.e. the efficiency of catching Species 1 by Métier 2 are shown in the left column of Figure 4.2, where the bycatch harvesting intensity of Métier 2 (ν_{12}) is depicted along the horizontal axis. All other parameters including the preference for fish consumption are set according to Table 4.1. The progression of stock levels in response to increasing bycatch intensity further illustrate the previous result. Instead of the stock of Species 1 decreasing with increasing harvesting efficiency for that species, it is instead the stock of Species 2 that is more strongly affected. Stocks of Species 1 are even increasing for a large parameter range. This adjustment is caused by the economic actors optimising given each of the parametrisations. Higher harvesting efficiency of Métier 2 makes it more profitable, increasing the corresponding number of firms (keeping profits zero), and correspondingly increasing harvests of both species. The increased harvests drive down prices. Thereby, simultaneously, Métier 1

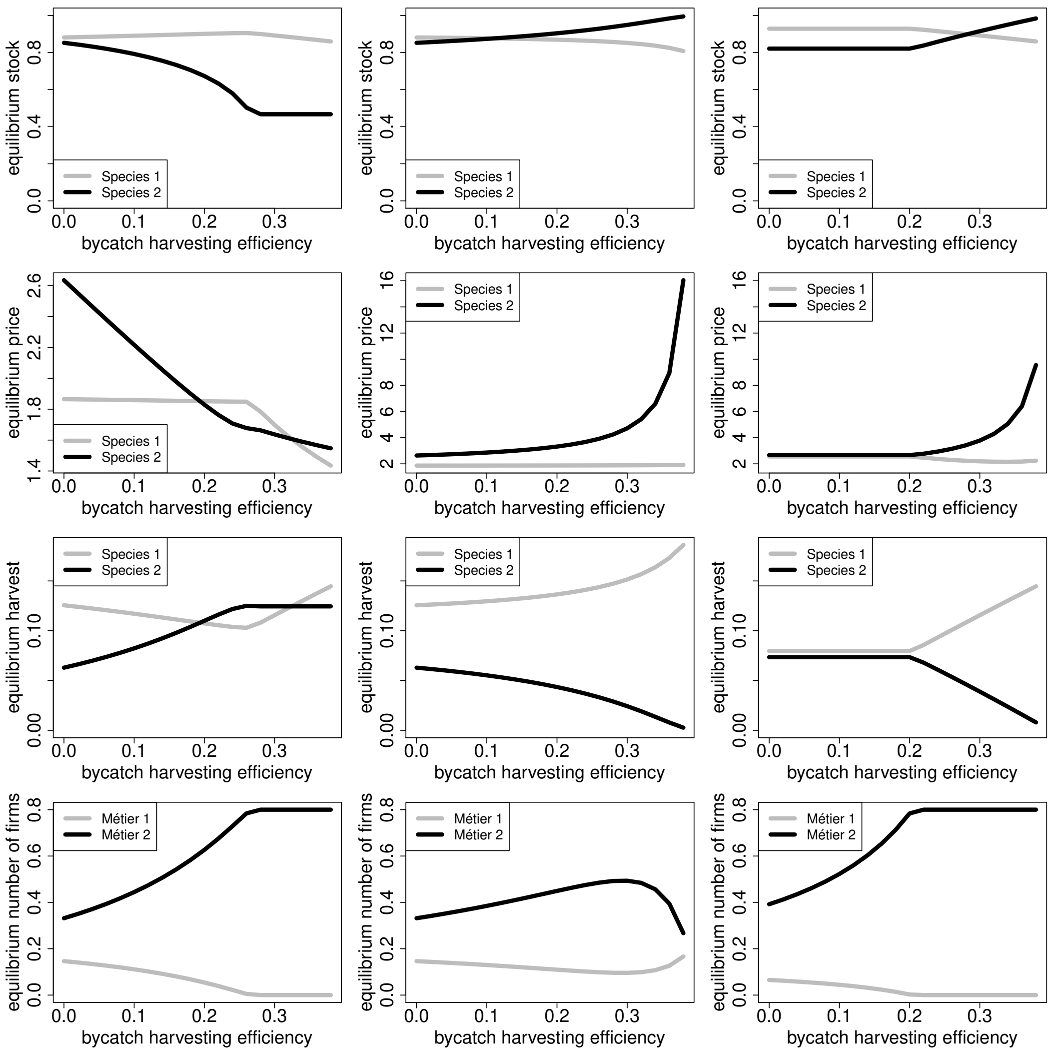

Figure 4.2: Interior equilibrium values of the model for stocks, prices, harvests and number of firms, given fully endogenous economic variables. Bycatch harvesting efficiency of Métier 2 (ν_{12}) is depicted along the horizontal axis. For the left column all other parameters are kept at their default values (Table 4.1). For the center and right columns, increases in the bycatch harvesting efficiency of Métier 2 are offset by decreases in the targeted harvesting efficiency of the same métier. Fixed costs of harvesting are adjusted to satisfy equation (4.36).

becomes comparatively less profitable, reducing the number of firms practising it. This in turn decreases harvesting pressure for Species 1. The latter effect overcompensates the direct effect of the increased harvesting efficiency for that species, yielding larger stocks. This type of adjustment breaks down when Métier 1 is completely abandoned ($\nu_{12} \geq 0.28$), which occurs when the condition for switching between cases (4.34) is met. In that domain, most indirect adjustment mechanisms are no longer active. Hence the direct effect of changes in the harvesting efficiency for the single métier can be observed.

The above effect is primarily driven by the increase in profitability of the métier with bycatch. However, given that the capacity of a fishing vessel is fixed. The increase in harvesting efficiency of a métier for a specific species may be associated with a decrease in the targeted harvest, keeping the total harvesting efficiency of a given métier $\sum_i \nu_{ik}$ constant. The long term steady states, when bycatch is introduced with this restriction on overall harvesting efficiency are shown in the centre column of Figure 4.2. These results are dominated by the direct effect of the changed harvesting efficiencies of Métier 2 (increasing for Species 1, decreasing for Species 2). The indirect effects, i.e. changes in the number of firms practising each of the métiers, are not strong enough in this case to overcome the direct effects. This shows that while the indirect effects can significantly alter outcomes, their strength depends on the specific manner in which bycatch changes harvesting properties. This can be seen as a limitation of the previous result.

An analytical result of the model is the condition on model parameters under which direct and indirect effects perfectly balance each other shown by equation (4.36). It specifies the relationship between métier fixed costs, harvesting efficiencies and returns to effort in harvesting that must hold for bycatch to not change long term steady states. The right column of Figure 4.2 shows the long run steady states of the model, with fix costs adjusted to satisfy condition (4.36). From these a limitation of this condition is immediately apparent: As before, indirect effects are only present while both métiers are practised. For bycatch intensities where only Métier 2 is practised, only the direct effects of changes in the harvesting efficiencies are left.

4.4 Discussion and Conclusion

In this paper the impact of bycatch is investigated in the context of ecosystem stocks developing over multiple periods with fishers and consumers acting independently to achieve their respective goals. The addition of the further source of interaction between harvested amounts of different species causes significant changes in model dynamics and equilibria. These changes are partly due to the direct effect of the increased total harvesting efficiency for individual species and partly due to indirectly caused changes in harvesting effort by fishers. With the model presented in this paper it is possible to investigate both direct and indirect effects simultaneously and determine their relative importance. The model presented is to my knowledge the first to include interactions between harvested species within the ecosystem, in harvesting and in consumer demand in a single analytically solvable model.

The main adjustment mechanism within the model, causing indirect effects on harvesting pressure, is through prices for individual species on the consumer market and fleet sizes. Based on straight forward relationships between ecosystem stocks, harvesting costs and prices, the latter adjust to changing stocks, varying over time and parametrisations. Consumer demand in turn takes into account not only the prices of individual species but also of substitutes. Fleet sizes then adjust in order for supply to meet demand. Independently of bycatch, this effect has the potential to cause significantly increased harvesting pressures on individual species, as the availability of others decline (Quaas and Requate, 2013). With the inclusion of bycatch this effect is exasperated, as increased prices not only increase harvesting pressures for the individual species, but also for bycatch species.

In much of the literature concerning multi-species fisheries these indirect effects are either omitted either by only considering single periods or by the assumption that prices do not respond to changes in harvests even if multiple periods are considered (e.g.Herrera (2005); Singh and Weninger (2009); Holland (2010)). Where the focus is entirely on the short term choices of fishers (e.g. Boyce (1996); Abbott and Wilen (2009)) this is a reasonable approach. The fisher choice problem within this paper is modelled in a similar way. But doing so, without a dynamic component in the model, precludes the analysis of longer term implications of the harvesting choices thereby derived. Conversely, the literature focused on the importance of consumer choice in multi-species fisheries have so far omitted bycatch (e.g. Baumgärtner et al. (2011); Quaas and Requate (2013)). The main contribution of this paper to the literature then is in demonstrating the importance of these interrelated interactions between harvested species and identifying a special case where these effects cancel each other out. This cancelation of effects rests on the assumption of free entry and exit on the fisheries market. Any barriers to entry, such as long term capital investments into vessels, would negate this result.

Hence, with regard to the development of management methods using economic models, aside from the special cases given by the conditions for no effect of bycatch, it appears to be necessary to take not only bycatch into account, but also the other sources of interaction between different species identified in this paper. If management measures are designed without these considered, the decision maker is implicitly under the impression that each species can be managed independently. However, due to these avenues of interaction between different species, a policy aimed at one will have cross-impacts on other species present in the ecosystem. The most likely result of this would be over-harvesting. For example, consider an abundant species being harvested by a métier that, unknown to the decision maker, also has a large bycatch of a more fragile species. In this case the determined management measure on practising that métier would be too lax, leading to over-fishing of the bycatch species. To avoid such outcomes, this model can be used to determine optimal fisheries management while taking bycatch and its direct and indirect effects into account.

The answer to the question posed in the title, if bycatch should be considered in modelling the interactions of fisheries, fishers and consumers therefore is the classical economist's answer: "It depends". It depends on the strength of the bycatch inherent in the métiers to be modelled. It also depends on the variables of interest to the modeller. While the error made for stocks, harvests and prices by omitting bycatch may be small, or even zero in special cases, it may be large for the number of firms. It may even change qualitative results such as the survival of species and which métiers are practised. While changes in the number of active firms are not of immediate importance regarding ecosystem management, they imply changes in employment which tends to be important to decisions makers in general. This is especially the case where the number of firms is declining, implying decreased opportunity for employment in this sector. As the condition for bycatch to have no effect on stocks, harvests and prices is quite narrow a more general answer is "yes".

Appendices

4.A The Firm Optimisation Problem

In the following, vector notation is used to simplify the equations. For this the following definition is needed.

$$\chi = \begin{pmatrix} \ddots & & 0 \\ & \chi_i & \\ 0 & & \ddots \end{pmatrix} \tag{4.37}$$

Furthermore as above the following abbreviation is used.

$$\chi_i = \chi(x_i) \tag{4.38}$$

The effort level is determined by maximizing profits.

$$e_k^{**} = \arg \max_{e_k} \vec{P}^{\intercal} \chi \vec{\nu}_k e_k^{\epsilon} - \omega e_k - \phi_k \tag{4.39}$$

The resulting first order condition is:

$$\epsilon \vec{P}^{\intercal} \chi \vec{\nu}_k e_k^{\epsilon - 1} - \omega = 0 \tag{4.40}$$

Rearranging yields the optimal harvesting effort level per métier and region.

$$e_k^{**} = \left(\frac{\epsilon \vec{P}^{\intercal} \chi \vec{\nu}_k}{\omega} \right)^{\frac{1}{1-\epsilon}} \tag{4.41}$$

As perfect markets are assumed in the model, market pressure will drive profits to zero. These market processes are not observable in the model's results, as they are assumed to happen instantaneously and only the resulting market equilibrium is calculated.

The zero profit condition reads:

$$\vec{P}^{\intercal} \chi \vec{\nu}_k e_k^{\epsilon} - \omega e_k = \phi_k \tag{4.42}$$

Rearranging of (4.41) and substituting into a rearranged (4.42) yields the optimal market equilibrium effort level. Note that this does not imply an equilibrium in the ecosystem stock change, but merely an equilibrium in market entry and exit of harvesting firms.

$$
\begin{aligned}
(4.41) \Leftrightarrow \quad && e_k^{1-\epsilon} &= \frac{\epsilon \vec{p}^{\intercal} \left(\vec{h}_k \chi \right)}{\omega} \\
(4.42) \Leftrightarrow \quad && \frac{\epsilon \vec{p}^{\intercal} \left(\vec{h}_k \chi \right)}{\omega} e_k^{\epsilon} - e_k \epsilon &= \frac{\phi_k}{\omega} \epsilon \\
\Leftrightarrow \quad && e_k (1 - \epsilon) &= \frac{\phi_k}{\omega} \epsilon \\
\Leftrightarrow \quad && e_k^* &= \frac{\phi_k}{\omega} \frac{\epsilon}{1 - \epsilon} \qquad (4.43)
\end{aligned}
$$

Optimal market-equilibrium effort decreases with wages. This is to be expected, as increasing wages imply that the firm can not afford as much labour. The model does not allow for substitution into variable capital. There is only fixed capital, covered by fixed costs. Furthermore, increasing fixed costs increases equilibrium effort level. This can be explained by increased fixed costs implying that more effort is needed to reach break-even. This ignores the possibility of not producing using a certain technology, however.

4.B The Household Optimisation Problem

4.B.1 All Métiers Practised

In the case where no non–negativity conditions are binding, the household optimisation problem reads as follows:

$$\max_{Q,y} U(Q, y) \text{ s.t. } \omega = y + \sum_{i=1}^{\bar{i}} p_i q_i \tag{4.44}$$

The corresponding Lagrangian function:

$$\mathcal{L}(Q, y) = U(Q, y) - \lambda(\omega - y - \sum_{i=1}^{\bar{i}} p_i q_i) \tag{4.45}$$

The resulting first order conditions:

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}y} = 1 + \lambda \qquad = 0 \tag{4.46}$$

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}q_{i'}} = \alpha q_{i'}^{\frac{\sigma-1}{\sigma}-1} \left(\sum_{i=1}^{\bar{i}} q_i^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} + \lambda p_{i'} \qquad = 0 \tag{4.47}$$

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\lambda} = \omega - y - \sum_{i=1}^{\bar{i}} p_i q_i \qquad = 0 \tag{4.48}$$

From (4.46) it trivially follows that $\lambda = -1$. This can be used in (4.47), which can then be rearranged to find the demand function for each harvested species as follows.

$$
\begin{aligned}
(4.47) \Leftrightarrow \quad & \alpha q_{i'}^{\frac{\sigma-1}{\sigma}-1} \left(\sum_{i=1}^{\bar{i}} q_i^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} = p_{i'} \\
\Leftrightarrow \quad & \alpha q_{i'}^{\frac{\sigma-1}{\sigma}-1} Q^{\frac{\eta-1}{\eta}-\frac{\sigma-1}{\sigma}} = p_{i'} && (4.49) \\
\Leftrightarrow \quad & \alpha q_{i'}^{-\frac{1}{\sigma}} Q^{\frac{\eta-1}{\eta}-\frac{\sigma-1}{\sigma}} = p_{i'} && (4.50) \\
\Leftrightarrow \quad & \left(\alpha Q^{\frac{\eta-1}{\eta}-\frac{\sigma-1}{\sigma}} \right)^{1-\sigma} q_{i'}^{\frac{\sigma-1}{\sigma}} = p_{i'}^{1-\sigma} \\
\Leftrightarrow \quad & \left(\alpha Q^{\frac{\eta-1}{\eta}-\frac{\sigma-1}{\sigma}} \right)^{1-\sigma} \underbrace{\sum_{i'=1}^{\bar{i}} q_{i'}^{\frac{\sigma-1}{\sigma}}}_{Q^{\frac{\sigma-1}{\sigma}}} = \sum_{i'=1}^{\bar{i}} p_{i'}^{1-\sigma} \\
\Leftrightarrow \quad & \alpha^{1-\sigma} Q^{(1-\sigma)\left(\frac{1}{\eta}\right)} = \sum_{i'=1}^{\bar{i}} p_{i'}^{1-\sigma} \\
\Leftrightarrow \quad & \left(\alpha Q^{\frac{1}{\eta}} \right)^{1-\sigma} = \sum_{i'=1}^{\bar{i}} p_{i'}^{1-\sigma} \\
\Leftrightarrow \quad & \alpha Q^{\frac{1}{\eta}} = \underbrace{\left(\sum_{i'=1}^{\bar{i}} p_{i'}^{1-\sigma} \right)^{\frac{1}{1-\sigma}}}_{P} \\
\Leftrightarrow \quad & Q = \alpha^{\eta} P^{-\eta} && (4.51)
\end{aligned}
$$

Hereby a price index P is used.

$$P = \left(\sum_{i'=1}^{\bar{i}} p_{i'}^{1-\sigma} \right)^{\frac{1}{1-\sigma}} \tag{4.52}$$

(4.51) can itself be substituted into (4.49) to finally obtain the demand function (4.53).

$$\begin{aligned}
(4.49) \Leftrightarrow \qquad & \alpha q_i^{\frac{1}{\sigma}} \left(\alpha^\eta P^{-\eta}\right)^{\frac{\eta-1}{\eta} - \frac{\sigma-1}{\sigma}} = p_i \\
\Leftrightarrow \qquad & q_i = \alpha^\eta p_i^{-\sigma} P^{\sigma-\eta} \\
\Leftrightarrow \qquad & q_i = \alpha^\eta p_i^{-\sigma} \left(\sum_{i'=1}^{\bar{i}} p_{i'}^{1-\sigma} \right)^{\frac{\sigma-\eta}{1-\sigma}} \qquad (4.53)
\end{aligned}$$

4.B.2 Prices, All Métiers Practised

Given Assumption 1 and the zero profit condition, prices are equal to unit costs in production. These are determined by solving the zero profit conditions of all $\bar{k}$ métiers simultaneously.

First the optimal effort level satisfying the individual zero profit conditions (4.43) is plugged back into the respective zero profit conditions.

$$\begin{aligned}
& \underbrace{\vec{p}'\chi\vec{\nu}_k \left(\overbrace{\frac{\phi_k}{\omega} \frac{\epsilon}{1-\epsilon}}^{e_k^*} \right)^{\epsilon}}_{\text{revenue}} = \underbrace{\omega \overbrace{\frac{\phi_k}{\omega} \frac{\epsilon}{1-\epsilon}}^{e_k^*}}_{\text{wage costs}} + \underbrace{\phi_k}_{\text{fixed costs}} \\
\Leftrightarrow \qquad & \vec{p}'\chi\vec{\nu}_k \left(\frac{\phi_k}{\omega} \frac{\epsilon}{1-\epsilon} \right)^{\epsilon} = \phi_k \left(1 + \frac{\epsilon}{1-\epsilon} \right) \\
\Leftrightarrow \qquad & \vec{p}'\chi\vec{\nu}_k = \phi_k \left(1 + \frac{\epsilon}{1-\epsilon} \right) \left(\frac{\phi_k}{\omega} \frac{\epsilon}{1-\epsilon} \right)^{-\epsilon} \qquad (4.54)
\end{aligned}$$

Equation (4.54) above represents a system of $\bar{k}$ linear equations. This can be used to determine the $\bar{i}$ prices p_i. However, this requires that $\bar{k} = \bar{i}$. Writing out the vector multiplications makes the linearity more easily apparent.

$$(4.54) \Leftrightarrow \sum_{i=1}^{\bar{i}} p_i \chi_i(\vec{x}) \nu_{ik} = \underbrace{\phi_k \left(1 + \frac{\epsilon}{1-\epsilon}\right) \left(\frac{\phi_k}{\omega} \frac{\epsilon}{1-\epsilon}\right)^{-\epsilon}}_{{}^p b_k} \tag{4.55}$$

To solve the system, it is rearranged as follows:

$${}^p A \, \vec{p} = {}^p \vec{b} \tag{4.56}$$

The top left index is used to denote that this LSE (linear system of equations) is used to solve for prices, as opposed to the LSE used to determine the number of firms below.

$${}^p A = \nu^\intercal \chi \tag{4.57}$$

$${}^p \vec{b} = \begin{pmatrix} {}^p b_1 \\ \vdots \\ {}^p b_{\bar{k}} \end{pmatrix} \tag{4.58}$$

$${}^p b_k = \phi_k \left(1 + \frac{\epsilon}{1-\epsilon}\right) \left(\frac{\phi_k}{\omega} \frac{\epsilon}{1-\epsilon}\right)^{-\epsilon} \tag{4.59}$$

Prices can then be easily solved for.

$$\begin{aligned} \vec{p} &= {}^p A^{-1} \, {}^p \vec{b} \\ &= \chi^{-1} (\nu^\intercal)^{-1} \, {}^p \vec{b} \end{aligned} \tag{4.60}$$

Thereby prices are fully determined.

4.B.3 Number of Firms, All Métiers Practised

Starting from the goods market clearing conditions for each of the species the problem of determining the numbers of firms can be transformed into a system of linear equations and solved as such.

$$
\begin{aligned}
& & H_i &= q_i(\vec{p}) \\
\Leftrightarrow & & \sum_{k=1}^{\bar{k}} n_k \chi(x_i) \nu_{ik} e_k^{*\epsilon} &= q_i(\vec{p}) \\
\Leftrightarrow & & \frac{q_i(\vec{p})}{\chi(x_i)} &= \sum_{k=1}^{\bar{k}} n_k \nu_{ik} e_k^{*\epsilon} \qquad (4.61)
\end{aligned}
$$

Represented as a LSE:

$$
{}^{n}A \; \vec{n} = {}^{n}\vec{b} \tag{4.62}
$$

with

$$
{}^{n}A = \nu \;\; \mathrm{diag}(\vec{e^{*\epsilon}})
$$

and

$$
\begin{aligned}
& & {}^{n}\vec{b} &= \chi^{-1}(\vec{x}) \; \vec{q}(\vec{p}) \\
\Leftrightarrow & & {}^{n}b_i &= \chi^{-1}(x_i) \; q_i(\vec{p})
\end{aligned}
$$

.

Solving for n yields:

$$
\vec{n} = {}^{n}A^{-1} \;\; {}^{n}\vec{b} \tag{4.63}
$$

4.B.4 One Métier Practised

The demand for the bundle provided by the active firm is derived by using the fact that the number of active firms for all other métiers is zero, in the optimality conditions of the household optimisation problem. Let there exist a single métier with positive active firms ($n_k > 0$) and let all other métiers have zero active firms ($n'_k = 0 \;\; \forall k \in \{[1,\bar{k}] \setminus k'\}$). From (4.23) it follows that $\lambda_k = 0$.

$$
\begin{aligned}
(4.20) \Leftrightarrow \quad & 0 = \frac{\mathrm{d}\mathcal{L}(\vec{n}}{\mathrm{d}n_k} \\
\Leftrightarrow \quad & 0 = \lambda_k - c_k + \alpha \Bigg(\sum_{i=1}^{\bar{i}} \Big(\sum_{k=1}^{\bar{k}} n_k h_{ik}(x_i) \Big)^{\frac{\sigma-1}{\sigma}} \Bigg)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} \\
& \sum_{i=1}^{\bar{i}} h_{ik}(x_i) \Big(\sum_{k=1}^{\bar{k}} n_k h_{ik}(x_i) \Big)^{\frac{\sigma-1}{\sigma}-1}
\end{aligned}
$$

using $n'_k = 0$ and $\lambda_k = 0$

$$
\begin{aligned}
\Leftrightarrow \quad & 0 = 0 - c_k + \alpha \Bigg(\sum_{i=1}^{\bar{i}} \big(n_k h_{ik}(x_i) \big)^{\frac{\sigma-1}{\sigma}} \Bigg)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} \sum_{i=1}^{\bar{i}} h_{ik}(x_i) \big(n_k h_{ik}(x_i) \big)^{\frac{\sigma-1}{\sigma}-1} \\
\Leftrightarrow \quad & 0 = -c_k + \alpha \Bigg(\sum_{i=1}^{\bar{i}} \big(n_k h_{ik}(x_i) \big)^{\frac{\sigma-1}{\sigma}} \Bigg)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} \sum_{i=1}^{\bar{i}} h_{ik}(x_i)^{\frac{\sigma-1}{\sigma}} n_k^{\frac{\sigma-1}{\sigma}-1} \\
\Leftrightarrow \quad & 0 = -c_k + \alpha \Bigg(\sum_{i=1}^{\bar{i}} n_k^{\frac{\sigma-1}{\sigma}} h_{ik}(x_i)^{\frac{\sigma-1}{\sigma}} \Bigg)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} n_k^{\frac{\sigma-1}{\sigma}-1} \sum_{i=1}^{\bar{i}} h_{ik}(x_i)^{\frac{\sigma-1}{\sigma}} \\
\Leftrightarrow \quad & 0 = -c_k + \alpha n_k^{\frac{\sigma-1}{\sigma}\left(\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1\right)} n_k^{\frac{\sigma-1}{\sigma}-1} \frac{\eta}{\eta-1} \Bigg(\sum_{i=1}^{\bar{i}} h_{ik}(x_i)^{\frac{\sigma-1}{\sigma}} \Bigg)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} \\
& \sum_{i=1}^{\bar{i}} h_{ik}(x_i)^{\frac{\sigma-1}{\sigma}} \\
\Leftrightarrow \quad & 0 = -c_k + \alpha n_k^{-\frac{1}{\eta}} \Bigg(\sum_{i=1}^{\bar{i}} h_{ik}(x_i)^{\frac{\sigma-1}{\sigma}} \Bigg)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}}
\end{aligned}
$$

$$
\Leftrightarrow \quad n_k^{-\frac{1}{\eta}} = c_k \alpha^{-1} \Bigg(\sum_{i=1}^{\bar{i}} h_{ik}(x_i)^{\frac{\sigma-1}{\sigma}} \Bigg)^{-\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}} \tag{4.64}
$$

$$
\Leftrightarrow \quad n_k = c_k^{-\eta} \alpha^{\eta} \Bigg(\sum_{i=1}^{\bar{i}} h_{ik}(x_i)^{\frac{\sigma-1}{\sigma}} \Bigg)^{\frac{(\eta-1)\sigma}{\sigma-1}} \tag{4.65}
$$

Equation (4.65) relates the number of bundles of type k demanded by the household. The number of goods demanded by the household follows from the goods market clearing condition (4.12).

$$
\begin{aligned}
q_i &= n_k h_{ik}(x_i) \\
q_i &= c_k^{-\eta}\alpha^{\eta}\left(\sum_{i=1}^{\bar{i}} h_{ik}(x_i)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{(\eta-1)\sigma}{\sigma-1}} \nu_{ik} e_k^{*\epsilon}\chi_i \\
q_i &= (e_k^{*}\omega + \phi_k)^{-\eta}\alpha^{\eta}\left(\sum_{i=1}^{\bar{i}} h_{ik}(x_i)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{(\eta-1)\sigma}{\sigma-1}} \nu_{ik} e_k^{*\epsilon}\chi_i
\end{aligned} \tag{4.66}
$$

4.B.5 Condition for Only One Métier Practised

In the following the condition for a single métier is derived. Without loss of generality this is done for Métier 1. Given Assumption 4 let $n_1 = 0$ and hence $\lambda_1 > 0$ while $n_2 > 0$ and $\lambda_2 = 0$.

Starting from (4.20) for Métier 1:

$$
\begin{aligned}
0 = \lambda_1 - c_1 + \alpha &\left(\sum_{i=1}^{\bar{i}}\left(\sum_{k=1}^{\bar{k}} n_k h_{ik}(x_i)\right)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} \\
&\sum_{i=1}^{\bar{i}}\left[h_{i1}(x_i)\left(\sum_{k=1}^{\bar{k}} n_k h_{ik}(x_i)\right)^{\frac{\sigma-1}{\sigma}-1}\right]
\end{aligned}
$$

Using Assumption 4 and assuming without loss of generality that $n_1 = 0$ and hence $\lambda_1 > 0$ while $n_2 > 0$ and $\lambda_2 = 0$.

$$
\begin{aligned}
\Rightarrow \quad & 0 = \lambda_1 - c_1 + \alpha\left(\sum_{i=1}^{\bar{i}}\left(n_2 h_{i2}(x_i)\right)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} \sum_{i=1}^{\bar{i}}\left[h_{i1}(x_i)\left(n_2 h_{i2}(x_i)\right)^{\frac{\sigma-1}{\sigma}-1}\right] \\
\Leftrightarrow \quad & -\lambda_1 = n_2^{\frac{\sigma-1}{\sigma}\left(\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1\right)}\alpha\left(\sum_{i=1}^{\bar{i}} h_{i2}(x_i)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} n_2^{\frac{\sigma-1}{\sigma}-1}\sum_{i=1}^{\bar{i}}\left[h_{i1}(x_i)h_{i2}(x_i)^{\frac{\sigma-1}{\sigma}-1}\right] - c_1 \\
\Leftrightarrow \quad & -\lambda_1 = n_2^{-\frac{1}{\eta}}\alpha\left(\sum_{i=1}^{\bar{i}} h_{i2}(x_i)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} \sum_{i=1}^{\bar{i}}\left[h_{i1}(x_i)h_{i2}(x_i)^{\frac{\sigma-1}{\sigma}-1}\right] - c_1
\end{aligned}
$$

The factor $n_2^{1-\eta}$ can be substituted by (4.64), due to Assumption 4, I.e. because Métier 2 is the only métier practised.

$$
\begin{aligned}
\Rightarrow \quad -\lambda_1 &= \overbrace{c_2 \alpha^{-1} \left(\sum_{i=1}^{\bar{i}} h_{i2}(x_i)^{\frac{\sigma-1}{\sigma}} \right)^{-\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}}}^{n_2^{-\frac{1}{\eta}}} \alpha \left(\sum_{i=1}^{\bar{i}} h_{i2}(x_i)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} \\
&\quad \sum_{i=1}^{\bar{i}} \left[h_{i1}(x_i) h_{i2}(x_i)^{\frac{\sigma-1}{\sigma}-1} \right] - c_1 \\
\Leftrightarrow \quad -\lambda_1 &= c_2 \left(\sum_{i=1}^{\bar{i}} h_{i2}(x_i)^{\frac{\sigma-1}{\sigma}} \right)^{-1} \sum_{i=1}^{\bar{i}} \left[h_{i1}(x_i) h_{i2}(x_i)^{\frac{\sigma-1}{\sigma}-1} \right] - c_1
\end{aligned}
$$

Substitute (4.15) and (4.8) for c_k and $h_{ik}(x_i)$.

$$
\begin{aligned}
\Rightarrow \quad -\lambda_1 &= (\phi_2 + \omega e_2^*) \left(\sum_{i=1}^{\bar{i}} (\chi_i \nu_{i2} e_2^*)^{\frac{\sigma-1}{\sigma}} \right)^{-1} \sum_{i=1}^{\bar{i}} \left[(\chi_i \nu_{i1} e_1^*) (\chi_i \nu_{i2} e_2^*)^{\frac{\sigma-1}{\sigma}-1} \right] - (\phi_1 + \omega e_1^*) \\
\Leftrightarrow \quad -\lambda_1 &= (\phi_2 + \omega e_2^*) e_2^{*\frac{1-\sigma}{\sigma}} \left(\sum_{i=1}^{\bar{i}} (\chi_i \nu_{i2})^{\frac{\sigma-1}{\sigma}} \right)^{-1} e_1^* e_2^{*\frac{\sigma-1}{\sigma}-1} \sum_{i=1}^{\bar{i}} \left[(\chi_i \nu_{i2})^{\frac{\sigma-1}{\sigma}} \frac{\nu_{i1}}{\nu_{i2}} \right] - \phi_1 - \omega e_1^* \\
\Leftrightarrow \quad -\lambda_1 &= e_1^* \left(\frac{\phi_2}{e_2^*} + \omega \right) \left(\sum_{i=1}^{\bar{i}} (\chi_i \nu_{i2})^{\frac{\sigma-1}{\sigma}} \right)^{-1} \sum_{i=1}^{\bar{i}} \left[(\chi_i \nu_{i2})^{\frac{\sigma-1}{\sigma}} \frac{\nu_{i1}}{\nu_{i2}} \right] - \phi_1 - \omega e_1^*
\end{aligned}
$$

Substitute (4.7) for e_k^*.

$$
\begin{aligned}
\Rightarrow \quad -\lambda_1 &= \left(\frac{\phi 1}{\omega} \frac{\epsilon}{1-\epsilon} \right) \left(\frac{\phi_2 \omega}{\phi_2} \frac{1-\epsilon}{\epsilon} + \omega \right) \left(\sum_{i=1}^{\bar{i}} (\chi_i \nu_{i2})^{\frac{\sigma-1}{\sigma}} \right)^{-1} \sum_{i=1}^{\bar{i}} \left[(\chi_i \nu_{i2})^{\frac{\sigma-1}{\sigma}} \frac{\nu_{i1}}{\nu_{i2}} \right] \\
&\quad - \phi_1 \left(1 + \frac{\epsilon}{1-\epsilon} \right) \\
\Leftrightarrow \quad -\lambda_1 &= \underbrace{\phi_1 \left(1 + \frac{\epsilon}{1-\epsilon} \right)}_{c_1} \left(\sum_{i=1}^{\bar{i}} (\chi_i \nu_{i2})^{\frac{\sigma-1}{\sigma}} \right)^{-1} \sum_{i=1}^{\bar{i}} \left[(\chi_i \nu_{i2})^{\frac{\sigma-1}{\sigma}} \frac{\nu_{i1}}{\nu_{i2}} \right] \underbrace{-\phi_1 \left(1 + \frac{\epsilon}{1-\epsilon} \right)}_{-c_1} \\
\Leftrightarrow \quad -\lambda_1 &= c_1 \left(\left(\sum_{i=1}^{\bar{i}} (\chi_i \nu_{i2})^{\frac{\sigma-1}{\sigma}} \right)^{-1} \sum_{i=1}^{\bar{i}} \left[(\chi_i \nu_{i2})^{\frac{\sigma-1}{\sigma}} \frac{\nu_{i1}}{\nu_{i2}} \right] - 1 \right) \\
\Leftrightarrow \quad -\lambda_1 &= c_1 \left(\left(\sum_{i=1}^{\bar{i}} (\chi_i \nu_{i2})^{\frac{\sigma-1}{\sigma}} \right)^{-1} \left(\sum_{i=1}^{\bar{i}} \left[(\chi_i \nu_{i2})^{\frac{\sigma-1}{\sigma}} \frac{\nu_{i1}}{\nu_{i2}} \right] - \sum_{i=1}^{\bar{i}} (\chi_i \nu_{i2})^{\frac{\sigma-1}{\sigma}} \right) \right) \\
\Leftrightarrow \quad -\lambda_1 &= c_1 \left(\sum_{i=1}^{\bar{i}} (\chi_i \nu_{i2})^{\frac{\sigma-1}{\sigma}} \right)^{-1} \left(\sum_{i=1}^{\bar{i}} (\chi_i \nu_{i2})^{\frac{\sigma-1}{\sigma}} \left(\frac{\nu_{i1}}{\nu_{i2}} - 1 \right) \right) \qquad (4.67)
\end{aligned}
$$

From (4.23) in conjunction with (4.67) it follows that

$$0 \geq \sum_{i=1}^{\bar{i}} (\chi_i \nu_{i2})^{\frac{\sigma-1}{\sigma}} \left(\frac{\nu_{i1}}{\nu_{i2}} - 1 \right) \tag{4.68}$$

where the equality holds only if (4.22) is not binding. Conversely the condition for Métier 1 not being employed is:

$$0 > \sum_{i=1}^{\bar{i}} (\chi_i \nu_{i2})^{\frac{\sigma-1}{\sigma}} \left(\frac{\nu_{i1}}{\nu_{i2}} - 1 \right) \tag{4.69}$$

4.C Conditions For No Effect of Bycatch

Given Assumption 4 (two species, two métiers) the equation determining the prices (4.28) can be written, for price of Species 1, in expanded form as

$$p_1(\nu) = (\chi_1 \chi_2)^{-1} (\nu_{11}\nu_{22} - \nu_{12}\nu_{21})^{-1} (\chi_2 \nu_{22}\, {}^p b_1 - \chi_2 \nu_{21}\, {}^p b_2) \tag{4.70}$$

As it is only relevant whether the price changes, not how it changes, and as prices are directly related through the demand function, this derivation can without loss of generality be done only for the price of Species 1.

It is assumed that the sum of the total harvesting efficiency of the métiers remains constant while adding bycatch to the model. For the price to remain constant the derivative of the price with respect to the increasing harvesting efficiency must equal the derivative with respect to the decreasing harvesting efficiency. Without loss of generality, let ν_{12} be the increasing and ν_{22} the decreasing harvesting efficiency.

$$\begin{aligned}
\frac{\mathrm{d}p_1}{\mathrm{d}\nu_{12}} &= \frac{\mathrm{d}p_1}{\mathrm{d}\nu_{22}} && (4.71)\\
\frac{\nu_{21}\left({}^p b_1 \nu_{22} - {}^p b_2 \nu_{21}\right)}{(\nu_{12}\nu_{21} - \nu_{11}\nu_{21})^2 \chi_1} &= \frac{\nu_{21}\left({}^p b_2 \nu_{11} - {}^p b_1 \nu_{12}\right)}{(\nu_{12}\nu_{21} - \nu_{11}\nu_{22})^2 \chi_1}\\
{}^p b_1 \nu_{22} - {}^p b_2 \nu_{21} &= {}^p b_2 \nu_{11} - {}^p b_1 \nu_{12}\\
{}^p b_1 (\nu_{22} + \nu_{12}) &= {}^p b_2 (\nu_{11} + \nu_{21})\\
\frac{{}^p b_1}{{}^p b_2} &= \frac{\nu_{11} + \nu_{21}}{\nu_{12} + \nu_{22}} && (4.72)
\end{aligned}$$

substitute ${}^{p}b$ with (4.59)

$$
\begin{aligned}
\frac{\phi_1\left(1+\frac{\epsilon}{1-\epsilon}\right)\left(\frac{\phi_k}{\omega}\frac{\epsilon}{1-\epsilon}\right)^{-\epsilon}}{\phi_k\left(1+\frac{\epsilon}{1-\epsilon}\right)\left(\frac{\phi_k}{\omega}\frac{\epsilon}{1-\epsilon}\right)^{-\epsilon}} &= \frac{\nu_{11}+\nu_{21}}{\nu_{12}+\nu_{22}} \\
\frac{\phi_1^{1-\epsilon}}{\phi_2^{1-\epsilon}} &= \frac{\nu_{11}+\nu_{21}}{\nu_{12}+\nu_{22}} \\
\frac{\phi_1}{\phi_2} &= \left(\frac{\nu_{11}+\nu_{21}}{\nu_{12}+\nu_{22}}\right)^{\frac{1}{1-\epsilon}} \qquad (4.73)
\end{aligned}
$$

Chapter 5

Vulnerablity of a Socio-Ecological System

Abstract: We develop an analytical framework to assess the vulnerabilities of a socio-ecological system (SES) and apply it to a bio-economic model. Our framework allows us to quantify the impact of multiple drivers on an SES, while distinguishing between impacts of positive and negative exposures. This distinction allows us to differentiate between drivers that improve and decrease well-being. Our findings provide insight into how to focus resources to counteract negative or enhance positive impacts. We apply this framework to a bio-economic model calibrated to the North Sea flatfish fishery. We quantify the vulnerabilities of fishers' profits to multiple drivers and identify which drivers have the most impact on profits. This work forms a bridge between the multidisciplinary area of vulnerability assessment and the bio-economic modelling domain, increasing the understanding and knowledge regarding the concept of vulnerability.
Keywords: Vulnerability assessment, bio-economic modelling, fisheries, adaptive capacity

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This chapter is based on the paper "Vulnerabilities of a Socio-Ecological System through the Lens of a Bio-Economic Model" presented at the 26th Annual Conference of the European Association of Environmental and Resource Economists by Quiroga and Blanz (2021). Now in submission to Ecological Economics.

5.1 Introduction

Socio-Ecological Systems (SESs), the combination of human activities and ecological processes, are influenced by a wide variety of drivers due to the breadth of their components and their interactions. Ecosystems face increasingly severe climatic events and social systems face economic, governmental, and social crises (Baggio et al., 2020; Cinner et al., 2013). Due to the interlinks between these two, forming the SES, a driver affecting one part can have impacts throughout the entire SES. Among this multitude of drivers it is challenging to establish priorities when attempting to mitigate harms or enhance benefits. To evaluate these impacts studies assess the vulnerability and adaptive capacity of an SES. However, most studies focus on the vulnerability of climate drivers (Salvucci and Santos, 2020; Reed et al., 2013; Berrouet et al., 2018), and non-climate drivers remain under-investigated (Berrouet et al., 2018; Thiault et al., 2019a). This is critical, since drivers from the socio-economic system, such as social preferences or market dynamics also affect the SES either by increasing poverty (Reed et al., 2013) or depleting resources (Möllmann et al., 2021; Baumgärtner et al., 2011). We provide the first analytical framework to quantify the vulnerabilities and adaptive capacities of multiple drivers on an SES distinguishing between beneficial and harmful impacts. Our framework also disentangles the vulnerabilities and adaptive capacities for each driver. This is important as it forms the foundation for policy makers to establish priorities and allocate resources efficiently.

The study of SESs is rooted in multidisciplinary research. Consequently, the literature presents several competing concepts of vulnerability and adaptive capacity (Berrouet et al., 2018; Janssen and Ostrom, 2006), with no consensus on their meaning (Gallopín, 2006; Ionescu et al., 2009; Hinkel, 2011). In general, vulnerability includes the attributes of social or ecological groups that enable them to cope with stressors. In the field of economics the focus lies on disturbances in future welfare, income, or consumption (World Bank, 2003). Vulnerability is further used to estimate possible future harm, and the potential for transformation of the system (Janssen and Ostrom, 2006; Berrouet et al., 2018). In most contexts the measure of harm involves normative judgments of what constitutes a good or bad state (Hinkel, 2011). Gallopín (2006) states that disturbances of an SES could also lead to beneficial transformations, and proposes the term positive vulnerability to describe them. So far, a framework assessing both positive and negative impacts on an SES is still lacking.

The ability of the SES or actors within it to adjust in response to drivers is generally termed adaptive capacity (Janssen and Ostrom, 2006). This concept is applied in multiple contexts and disciplines, leading to lack of clarity (Whitney et al., 2017). Most studies of adaptive capacity are based on indicators, such as access to assets, livelihoods or governance and institutions (Whitney et al., 2017; Reed et al., 2013). Basing an estimate of adaptive capacity on such indicators raises two issues: First, the indicators measure only the access to resources, not if those resources would be used. Second, they describe general adaptive capacities to deal with any harm and conceal driver-specific adaptation. The latter issue is relevant, as both drivers and adaptation are interconnected. The harm caused by one driver may impair the ability to respond to future drivers (McDowell and Hess, 2012; Thiault et al., 2019a). Identifying driver-specific adaptive capacities and comparing them remains a challenge.

In this paper we present a framework that (i) estimates the vulnerability and adaptive capacity in response to a single or multiple specific drivers, (ii) quantifies how the adaptive capacity influences vulnerability, and (iii) investigate harmful, and beneficial impacts of multiple drivers on an SES. Thereby we address the issues of overly general assessments of vulnerability, adaptive capacity and omitted beneficial changes. The proposed framework provides a mathematical structure to disentangle the vulnerability and adaptive capacity determined in case studies (Janssen and Ostrom, 2006).

We apply our framework using a bio-economic model as the mathematical structure facilitates implementation. Bio-economic models are useful in understanding particular trade-offs and feedbacks between economic and biological sub-systems. They allow understanding of the effects of consumer preferences on ecological aspects (Quaas and Requate, 2013; Baumgärtner et al., 2011), the concepts of resilience and sustainability (Derissen et al., 2011), and the relationship between social norms and dynamics of an ecological subsystem (Lade et al., 2013). We illustrate our analytical framework using a version of the bio-economic model developed by Blanz (2019). However, our framework applies to other models or contexts, offering a guideline for statistical models that establish relationships among outcome variables and drivers.

As a proof of concept, the framework is applied to a calibrated bio-economic model of the North Sea flatfish fishery. We determine the vulnerabilities and adaptive capacities of fishers' profits to multiple drivers, with both harmful and beneficial impacts. We show impacts of a driver propagating within the SES. Our results indicate that fishers' profits are most vulnerable to changes in plaice prices, returns to effort, stock harvesting efficiency of plaice, plaice stocks, and wages. Furthermore, a marginal increase in fixed costs decreases profits the most. Regarding adaptation, the fishery can better adapt to changes in household preferences and wages than other drivers evaluated. To our knowledge, this is the first time the vulnerabilities and adaptive capacities within an SES are individually quantified in response to multiple drivers. Also, the first time a bio-economic model is used to assess vulnerabilities. Our framework establishes trade-offs between the ecological and economic sub-systems identifying the most relevant drivers for decision-makers to allocate resources efficiently.

5.2 The Interdisciplinary Field of Vulnerability Assessments

This paper combines three fields of literature, the interdisciplinary field of vulnerability assessments in Socio-Ecological Systems (SESs), the microeconomics view of vulnerability, and the bio-economic modelling domain. We use mathematical modelling to build a formal structure based on definitions from the vulnerability assessments field and concepts of vulnerability in microeconomics and bio-economic modelling.

The interdisciplinary field of vulnerability assessments encompasses a variety of qualitative and quantitative methods to assess vulnerability (Berrouet et al., 2018; González-Mon et al., 2019). These methods mainly use the vulnerability definition described by the Intergovernmental Panel on Climate Change (IPCC) as it gained the most traction. In this definition the vulnerability of people's livelihoods to impacts of climate change depends on their exposure to climate impacts, their sensitivity (i.e. the extent to which their livelihood is affected by an impact), and their capacity to adapt to those impacts (IPCC, 2014). In the area of marine SESs many authors based their vulnerability assessment on this definition (Chen et al., 2020; Cinner et al., 2013; Marshall et al., 2013; Milner-Gulland, 2012; Willaert et al., 2019; Cabral et al., 2015; Thiault et al., 2019a). These studies identify threats related to causal processes and outcomes of exposure, sensitivity, and adaptive capacity. Most studies introduce economic and social variables but ignore market dynamics or consumption behaviour (Thiault et al., 2019a). This is important since these dynamics may affect the entire SES through interaction effects.

In the microeconomics field, the vulnerability concept is mostly applied to poverty dynamics, food security, or sustainable livelihoods at the household level (Moret, 2014). Hoddinott and Quisumbing (2010) define vulnerability as "*the likelihood that at a given time in the future, an individual will have a level of welfare below some norm or benchmark.*" (Hoddinott and Quisumbing, 2010, p. 72). Similarly, the World Bank (2003) defines vulnerability as the resilience against a shock resulting in a decline in well-being in terms of income and consumption at the household level.

In the bio-economics field, models are used to analyse welfare, income shocks and viability in an economic and ecological subsystem (Schuhbauer and Sumaila, 2016). Their mathematical representation provides insights into the interactions between ecological and economic systems (Baumgärtner et al., 2011; Quaas and Requate, 2013; Quaas et al., 2013). Additionally, they allow trade-offs between potentially conflicting objectives or constraints (Gourguet et al., 2013). Bio-economic models offer an understanding of the impact of society's preferences on resilience and sustainability (Quaas et al., 2013), by-catch effects in fisheries (Blanz, 2019), and relationships between social norms and ecological sub-systems (del Pilar Moreno-Sánchez and Maldonado, 2010; Lade et al., 2013). These models offer clear mathematical definitions that in other contexts are sometimes blurred by language.

We aim to formalize the vulnerability concept by combining these three branches of the literature. By formalization we mean using mathematical concepts that are independent of any knowledge domain and applicable to any system under consideration (Ionescu et al., 2009). Gallopín (2006); Hinkel (2011); Ionescu et al. (2009); Janssen and Ostrom (2006); Wolf et al. (2013) offer a wide discussion about the need to formalize the vulnerability concept. Vulnerability analyses are conducted without well-established meta-concepts, leading to multiple definitions of vulnerability (Wolf et al., 2013). Hence, a formalization of the concept helps to solve ambiguity and support a clear communication. To our knowledge only Ionescu et al. (2009) developed an approach to formalize the definition of vulnerability, focusing on vulnerability to climate change. We add to the literature by presenting a more general framework appropriate to any setting, and we apply it to a specific case study. We innovate by combining the general structure given by Ionescu et al. (2009) with the already built bio-economic modelling field. In our case study we also incorporate the microeconomics definition of vulnerability. We provide a novel way of framing vulnerability specifically in SES contexts.

5.3 Framework for Vulnerabilities Assessment

We define vulnerability *as a system's susceptibility to harm [or benefit] due to exposure and sensitivity to an internal or external change from the status-quo, and its adaptive capacity to respond to it.* Our definition is based on Chapin et al. (2010), and encompasses several descriptions in the literature, using exposure, sensitivity, and adaptive capacity (Johnson et al., 2016; IPCC, 2014; Halpern et al., 2012; Gallopín, 2006; Lauerburg et al., 2019). The literature, however, evaluates only the harmful impact of stressors. We deviate from these studies by also considering benefits generated from changes in drivers. Hence, we evaluate changes from the status-quo that cause harms or benefits to SESs. Hinkel (2011) mentions that most vulnerability frameworks involve a normative value judgment on the "badness" of a state. This judgment is made by the scientist, a difficult exercise since harm involves multiple dimensions and trade-offs. Using a mathematical structure to assess vulnerabilities allows us to evaluate positive and negative deviations from a status-quo, and thus avoid a value judgment of the effect of the driver on the SES. However, it generates a language concern since vulnerability is by definition a negative concept. To remain consistent with our framework structure linguistically we decide to follow Gallopín (2006) and use the term positive vulnerability to describe beneficial impacts generated by changes from the status-quo.

Our framework is designed to answer the question *the vulnerability of what to what?*[1]. Hence, the methodology encompasses two steps. Identification of (i) the system property under analysis (*of what*), and (ii) the driver (*to what*). The system property refers to the specific aspect of the SES considered. For example, in our case study, we investigate the *vulnerability of fisher profits to changes in e.g. wages* and other drivers. In the following, we present the formal definitions of drivers, exposure, sensitivity, adaptive capacity, and vulnerability.

[1]We follow Ionescu et al. (2009) who state that vulnerability is a relative property, hence it is the vulnerability *of* something *to* something.

5.3.1 Formalisation

Drivers

We define $\theta = (\theta_1, \ldots, \theta_D)$ as the vector of D drivers of the SES, for which the researcher wishes to investigate the impacts on a specific system property. For instance, θ_d can represent the value of an input in a certain process affecting the system property.

System Properties

We define $\psi(\theta) = (\psi_1(\theta), \ldots, \psi_P(\theta))$ as the P properties of the system under investigation. In the general case this is a vector valued function. With each entry of ψ representing one of the properties of the system. For a single property an individual function $\psi_p(\theta)$ can be evaluated. If the system is represented by a single property $\psi(\theta)$ becomes a scalar.

Adaptation

We define $\tau(\theta) = (\tau_1(\theta), \ldots, \tau_M(\theta))$ as the M adaptation variables of actors within the system. A system can have a single $\tau_m(\theta)$ or multiple $\tau(\theta)$ adaptation variables.

5.3.2 Exposure

Exposure to changes in drivers, or simply exposure, is the magnitude of change in any drivers affecting the system property. For determining vulnerability, the source of these events is not relevant, only their magnitude. This can either be evaluated for the entire vector of drivers or for individual drivers.

$$E(\theta, {}^0\theta) = \theta - {}^0\theta \tag{5.1}$$

$$E_d(\theta_d, {}^0\theta_d) = \theta_d - {}^0\theta_d \tag{5.2}$$

Each $E_d(\theta_d, {}^0\theta_d)$ depends on the magnitude of change in the driver d, where ${}^0\theta_d$ is the original value of the driver, and θ_d is the new state (Eq. (5.2)). The vector ${}^0\theta$ contains the initial values of all drivers. θ_d can be higher or lower than the initial state, resulting in a positive or negative exposure. If changes in a single driver, e.g. θ_d, are evaluated the vector of exposure contains zeros in all positions except for the change in θ_d in the dth position ($E(\theta', {}^0\theta) = (0, \ldots, \theta'_d - {}^0\theta_d, \ldots, 0)$).

5.3.3 Sensitivity

The sensitivity is the degree to which the system property is affected either adversely or beneficially by exposure to changes in drivers (IPCC, 2001), given their initial values and excluding any adaptation. The sensitivity to a given level of exposure may vary depending on the system property under analysis. We interpret this as the change on the system property given by a change in the driver (Eq.(5.3)).

We define continuous and absolute sensitivities regarding the impact on the system property. The absolute measure is useful when investigating the total impact considering the range of exposure levels of the driver. Marginal sensitivities show the rate of change in the system property given by a marginal change in driver.

Absolute

In Eq.(5.3) we evaluate the system properties (ψ) in two points, at the initial state of the drivers $\psi({}^0\theta)$ and at the new state $\psi(\theta)$. Depending on the data availability Eq. (5.3) can be evaluated in many values for each driver considered. For each property the sensitivity ψ_p is measured by the difference in the system property induced by the exposure, without adaptation. The absolute sensitivity can have positive or negative values, it depends on the effect of the driver on the system property. I.e., if $\psi_p(\theta)$ is greater than the value of the system property at the initial state ($\psi_p({}^0\theta)$) then the sensitivity with respect to that property $S_p(\theta, {}^0\theta)$ is positive, otherwise it is negative. is considered a stressor, otherwise a benefactor.

$$S(\theta, {}^0\theta) = \psi(\theta, \tau({}^0\theta)) - \psi({}^0\theta, \tau({}^0\theta)) \tag{5.3}$$

$$S_p(\theta, {}^0\theta) = \psi_p(\theta, \tau({}^0\theta)) - \psi_p({}^0\theta, \tau({}^0\theta)) \tag{5.4}$$

Marginal

The marginal sensitivities evaluate impacts on the system properties from marginal changes in a driver at a given point. It measures the impact of a marginal increase in exposure from this point disregarding non-linearities in responses to larger exposure levels. This is relevant when making policy choices that are robust to random shocks [2]. When multiple properties and drivers are evaluated simultaneously, the marginal form is the jacobian of Eq. (5.3). The entries s_{pd} give the marginal sensitivity of property p to a change in driver d. In the case only a single property is considered $P = 1$ the Jacobian matrix collapses to a vector of partial derivatives.

$$s(\theta, {}^0\theta) = \begin{pmatrix} \dfrac{\partial S_1(\theta, {}^0\theta)}{\partial \theta_1} & \cdots & \dfrac{\partial S_1(\theta, {}^0\theta)}{\partial \theta_D} \\ \vdots & \ddots & \vdots \\ \dfrac{\partial S_P(\theta, {}^0\theta)}{\partial \theta_1} & \cdots & \dfrac{\partial S_P(\theta, {}^0\theta)}{\partial \theta_D} \end{pmatrix} \tag{5.5}$$

$$s_{pd}(\theta, {}^0\theta) = \frac{\partial S_p(\theta, {}^0\theta)}{\partial \theta_d} = \frac{\partial \psi_p(\theta, \tau({}^0\theta))}{\partial \theta_d} \tag{5.6}$$

5.3.4 Adaptive Capacity

We define adaptive capacity as the ability of an element within an SES to adjust to changing external or internal drivers. Adaptation moderates harm or exploits beneficial opportunities (IPCC, 2014). In addition to the drivers, the system properties (ψ) also depend on $\tau(\theta)$, which corresponds to the endogenous behaviours in response to the drivers θ. The adaptive capacity measures how much an optimal response, adaptation, in response to a change in the drivers can improve the system property, compared to the outcome without an adaptation (Eq. (5.7)). Additionally, we also measure the amount of change in the endogenous behaviour that is necessary to achieve the optimal adaptation.

Absolute

Eq.(5.7) shows the difference between the system properties with an endogenous response to the drivers $\tau(\theta)$, and the initial behaviour $\tau({}^0\theta)$ with no response. In the case of multiple

[2] We follow Gallopín (2006) who defines sensitivity as change in the transformation of the system with respect to a change in the perturbation.

behaviour variables $\tau(\theta)$ is a vector. For instance, to assess the adaptive capacity *of* a community's well being *to* climate change, $\psi_p(\theta, \tau(\theta))$ corresponds to the system property under evaluation, i.e., community's well-being, a measure of the outcome. θ are drivers affected by climate change, and $\tau(\theta)$ reflects the community's actions affecting their well-being. $\tau(\theta)$ changes in response to the drivers θ. The community's well-being $\psi(\theta)$ can be some measure of utility, socio-economic or financial characteristics. The adaptive capacity is the benefit to the community of adapting to climate change, determined as the difference in well-being in the community before and after adaptation. If $\psi(\theta, \tau(\theta))$ is a vector of multiple properties being evaluated ${}^aA(\theta, {}^0\theta)$ is a vector valued function, where each entry corresponds to the changes in one of the properties.

$$\begin{aligned} {}^aA(\theta, {}^0\theta) &= \psi(\theta, \tau(\theta)) - \psi(\theta, \tau({}^0\theta)) \\ &= ({}^aA_1(\theta, {}^0\theta), ..., {}^aA_P(\theta, {}^0\theta)) \\ &= (\psi_1(\theta, \tau(\theta)) - \psi_1(\theta, \tau({}^0\theta)), ..., \psi_P(\theta, \tau(\theta)) - \psi_P(\theta, \tau({}^0\theta))) \end{aligned} \tag{5.7}$$

The change in behaviour in order to adapt is the difference in $\tau(\theta)$ due to the change in θ (Eq.(5.9)).

$$ {}^cA(\theta, {}^0\theta) = \tau(\theta) - \tau({}^0\theta) \tag{5.8}$$

$$ = (\tau_1(\theta) - \tau_1({}^0\theta), ..., \tau_M(\theta) - \tau_M({}^0\theta)) \tag{5.9}$$

Marginal

We consider three marginal measures for adaptive capacity. First, the marginal version Eq. 5.7 is the Jacobian with the elements ${}^aa_{pd}(\theta)$. The entry ${}^aa_{pd}(\theta)$ represents the change in the mitigation of sensitivity of the system property p given by a change in the adaptation behaviour (τ) due to a marginal change of the driver d (Eq. 5.10). Second, as the marginal adaptive capacity of Eq. (5.10) is zero in the zero exposure case we also consider the second derivatives of Eq. (5.7). The elements ${}^ba_{pd}(\theta)$ present the second partial derivatives of Eq. 5.7. This is the curvature of the adaptive capacity curve, the rate at which ${}^aa_{pd}(\theta)$ changes due to a marginal change in θ_d. Third, ${}^ca_{md}(\theta)$ is the marginal measure of ${}^cA(\theta,{}^0\theta)$. It shows the marginal optimal change of adaptation behaviour in τ_m, given a marginal increase in driver d(Eq. 5.13).

$$
\begin{aligned}
{}^a a_{pd}(\theta) &= \frac{\partial A_p\theta,{}^0\theta)}{\partial\,\theta_d} \\
&= \frac{\partial\psi_p(\theta,\tau(\theta))}{\partial\,\theta_d} - \frac{\partial\psi_p(\theta,\tau({}^0\theta))}{\partial\,\theta_d}
\end{aligned} \tag{5.10}
$$

$$
= v_{pd}(\theta) - s_{pd}(\theta) \tag{5.11}
$$

$$
\begin{aligned}
{}^b a_{pd}(\theta) &= \frac{\partial^2 A_{pd}(\theta,{}^0\theta)}{\partial^2\,\theta_d^2} \\
&= \frac{\partial^2\psi_{pd}(\theta,\tau(\theta))}{\partial^2\,\theta_d^2} - \frac{\partial^2\psi_{pd}(\theta,\tau({}^0\theta))}{\partial^2\,\theta_d^2} \\
&= \frac{\partial v_{pd}(\theta)}{\partial\theta_d} - \frac{\partial s_{pd}(\theta)}{\partial\theta_d}
\end{aligned} \tag{5.12}
$$

$$
{}^c a_{md}(\theta) = \frac{\partial\tau_m(\theta)}{\partial\,\theta_d} \tag{5.13}
$$

For instance, to assess the adaptive capacity *of* a community's well being *to* climate change, $\psi(\theta,\tau(\theta))$ represents a single measure of community's well being affected by climate change $(P = 1)$. Consider θ_1 a measurement of temperature and θ_2 precipitation $(\theta = (\theta_1,\theta_2))$. Let $\tau(\theta)$ be the adaptive actions that the community performs to affect their well being. Then ${}^a a_d(\theta)$ shows how the well being is affected by this change in the adaptive action given a marginal change in the driver θ_d. ${}^b a_d(\theta)$ represents the change of well being changes, due to adaptive behavioural changes with temperature or precipitation. If ${}^b a_2(\theta) < {}^b a_1(\theta)$, then adaptive capacity will build up quicker for temperature than for precipitation. Finally, ${}^c a_{md}(\theta)$ shows how a marginal change in the driver affects these adaptive actions, i.e, the optimal change in action given by a marginal change in temperature or precipitation. If ${}^c a_{m2}(\theta) > {}^c a_{m1}(\theta)$ then adaptation to precipitation requires a larger change in behaviour with respect to action m in order to adapt to precipitation than temperature. If there are multiple actions that can be adjusted to changing drivers these relationships may vary per action.

5.3.5 Vulnerability

The vulnerability combines exposure, sensitivity, and endogenous adaptive capacity. It is the overall changes of the system properties once exposed to the driver changes and endogenous adaptation occurs. Vulnerability measures the total impact of changes in drivers on the system properties. It is equal to sensitivity plus adaptive capacity. The latter is always positive. If sensitivity reduces the outcome of the system property, adaptive capacity counteracts this effect, otherwise enhances it.

Absolute

The system property is evaluated at the initial value of the drivers with no adaptation $\psi({}^0\theta, \tau({}^0\theta))$, and at the new values with adaptation $\psi(\theta, \tau(\theta))$. The difference between both is defined as vulnerability (Eq. (5.14)).

$$\begin{aligned} V(\theta, {}^0\theta) &= S(\theta, {}^0\theta) + {}^aA(\tau(\theta, {}^0\theta)) \\ &= \psi(\theta, \tau(\theta)) - \psi({}^0\theta, \tau({}^0\theta)) \end{aligned} \tag{5.14}$$

$$\begin{aligned} V_p(\theta, {}^0\theta) &= S_p(\theta, {}^0\theta) + {}^aA_p(\tau(\theta, {}^0\theta)) \\ &= \psi_p(\theta, \tau(\theta)) - \psi_p({}^0\theta, \tau({}^0\theta)) \end{aligned} \tag{5.15}$$

Marginal

The marginal vulnerability is the Jacobian of Eq. 5.14. The entries of the Jacobian are defined by Eq. 5.16. These show the change in the system property p with an optimal adaptation $\tau(\theta))$, given a marginal increase in driver θ_d. The marginal vulnerability evaluated at the zero exposure levels of the drivers ${}^0\theta$ will be equal to the marginal sensitivity, as the marginal adaptive capacity is zero at that point.

$$\begin{aligned} v_{pd}(\theta) &= \frac{\partial V_p(\theta, {}^0\theta)}{\partial\, \theta_d} = \frac{\partial \psi_p(\theta, \tau(\theta))}{\partial\, \theta_d} \\ &= s_{pd}(\theta) + {}^a a_{pd}(\theta) \end{aligned} \tag{5.16}$$

5.4 Case Study: North Sea Flatfish Fishery

We apply the framework to fishers' profitability in the North Sea flatfish fishery. The EU derives 32% of the total landings from the North Sea and the Eastern Arctic, accounting for the highest total landed value in Europe (Scientific , technical and economic committee for fisheries (STECF)., 2019). Historically, the most harvested species in this region by value are Atlantic cod, Atlantic mackerel, and Atlantic herring (Scientific , technical and economic committee for fisheries (STECF)., 2019). However, a variety of other species such as European plaice, Common sole, and Common shrimp account for one third of the economic value generated in the North Sea. Fishing pressure caused shifts in the ecosystem composition historically and further shifts are expected due to climate change. This region is identified as one of the 20 hot-spots of climate change globally (Pinnegar et al., 2016). Quante and Colijn (2016) show projections regarding increased sea level, ocean acidification, ocean temperature, and a decrease in primary production. This causes migration of the species, affecting the availability of resources to local fishing fleets, and reducing the overall 'carrying capacity' of the stock (Pinnegar et al., 2016).

The North Sea flatfish fishery is a multi-species fishery catching plaice, sole, cod, and other flatfish. The economic importance of fisheries in the North Sea led to over-fishing of some flatfish species. In this paper we focus on European Plaice (*Pleuronectes platessa*) and Common Sole (*Solea solea*), because they are the two principal flatfish species targeted by European fisheries (Etherton, 2015). Sole grows up to a length of 30cm, and plaice up to 33cm (Knijn et al., 1993). These species have endured the consequences of climate change, over-fishing, and pollution (Engelhard et al., 2011; Gattuso et al., 2018).

To promote the sustainability of the stock a policy was adopted regulating Total Allowable Catches (TACs), conservation areas, and mesh size (van Keeken et al., 2007; Engelhard et al., 2011; European Commission, 2014). TACs are in place since 1979 mostly restricting harvest of sole, while TACs for plaice have often been so large as to be non binding (Figure 5.1) (Daan, 1997). During the second half of the 20th century, the TACs decreased for plaice, in line with a recommended reduction in fishery mortality (Daan, 1997). In 1989, to allow the plaice population to recover, a protected area, the 'Plaice Box', is closed to trawling fisheries (an area on the Dutch and German coast). The Spawning Stock Biomass (SSB) for plaice decreases after this measure, attributed to a distribution shift caused by long term climate change and an increase in discards outside of the 'Plaice Box' (Engelhard et al., 2011; van Keeken et al., 2007) (Figure 5.1). The drop in the SSB for sole since 1990 was also caused by shifted distributions but strongly attributed to fishing pressure. The high price of sole makes it the preferred targeted fish compared to plaice (Engelhard et al., 2011), however, it is not possible to catch sole independently of plaice. In recent years the plaice stock (SSB) has recovered while sole shows a constant tendency (ICES, 2019b,a)

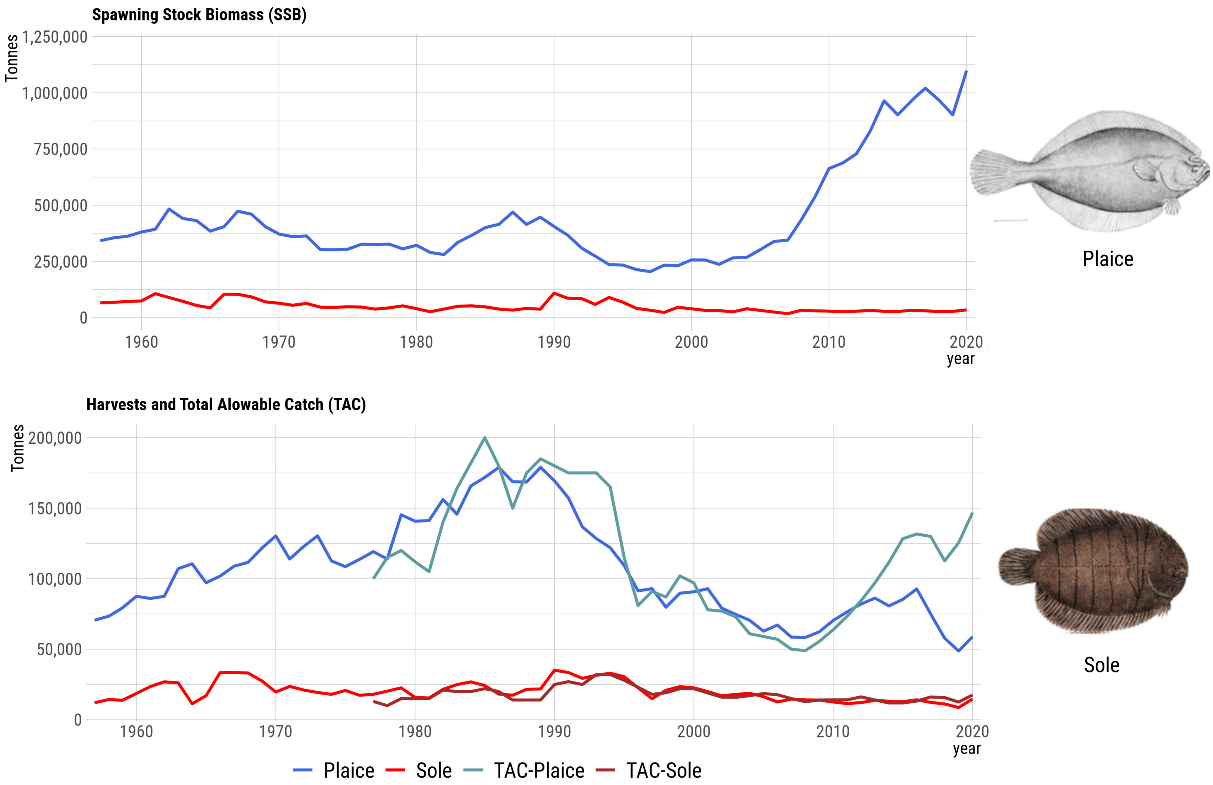

Figure 5.1: Spawning Stock Biomass (top), Harvests (Landings) and Total Allowable Catch (bottom) for plaice and sole between 1957-2020.

In the last decade, the average landings (harvests) of plaice by weight are approximately seven times larger than those of sole. However, because the price of sole is six times that of plaice, the two species' landings are roughly equal in value (Scientific , technical and economic committee for fisheries (STECF)., 2019). The main actors in this fishery are The Netherlands, Denmark, UK, Belgium, France, and Germany. Despite increases in costs net profits remain positive, except for the Belgian and German fleets between 2010-2017 (Scientific , technical and economic committee for fisheries (STECF)., 2019).

5.4.1 Bio-Economic Model

To apply the framework to our case study we use an existing bio-economic model (Blanz, 2019), with some modifications. We replace the logistic growth function, used to model stock change, with a Ricker-recruitment type growth function (Ricker, 1975). We also introduce weighting factors for each fish species in the household utility function to better reflect consumer preferences. With these modifications, the model embodies the peculiarities of the North Sea flatfish fishery (See the detailed description of the model in Appendix 5.A). A feature of the model is the introduction of simultaneous multi-species harvesting, i.e., fisheries target one species but in doing so catch other species. In our case study, the fishers behaviour is market-driven. Fishers mostly target sole because of its higher price, but in doing so they also catch plaice (Aarts and Poos, 2009). The model includes parameters that account for these characteristics to resemble observations.

The bio-economic model has three elements: (i) The ecosystem component includes harvests and the stock change, represented by the species growth function for plaice and sole. The stock levels are the system's state variables. The system's stable and non-stable steady-states depend on the stock change which results from ecosystem growth and harvests. (ii) The harvesting component includes an endogenous amount of fisheries firms comprising the fleets of two métiers[3]. The first targets plaice and the second sole with imperfect selectivity. The harvesting function depends on effort and stock availability. Firms maximize profits, derived from harvests, prices, variable and fixed costs. (iii) The household component consists of a representative household obtaining utility from fish consumption and manufactured goods. The household maximizes utility subject to a budget restriction and thereby determines the optimal quantities demanded and willingness to pay for each fish species.

The model assumes market-clearing, all goods produced are consumed (Eq. 5.39). In the long run a competitive market with free entry and exit, firms compete such that prices and total costs are equal. This leads to the zero profit assumption described in Eq. (5.34). The size of the fleets is determined satisfying the zero profit assumption and the optimal effort choice by fishing firms. The steady-states for stocks of each species in an open-access scenario are determined numerically. Our model resembles particular aspects

[3]Métier refers to a combination of vessel and gear type. In this paper we use a model with two species where the species sub-index i takes the value of 1 for plaice and 2 for sole. Similarly the sub-index k refers to the two fleets, where k=*1* refers to the fleet targeting plaice and k=*2* the fleet targeting sole.

of the North Sea flatfish fishery mainly catching plaice and sole. The model presents an abstraction of the multiple complexities embedded in this fishery, but still useful providing insights regarding the vulnerabilities we analyse.

5.4.2 Calibration of the Model

We calibrate the model to time series of stocks, harvests, and prices for the whole North Sea. For stocks and harvests, we use data on spawning stock biomass (SSB) and landings from 1957 to 2019 provided by the International Council for the Exploration of the Sea (ICES, 2019a,b). We use price data from the European Market Observatory for Fisheries and Aquaculture Products (EUMOFA) database for the years from 2000 to 2020. The ecosystem component is calibrated independently of the economic parts using the observed stock growth and harvests. Within the model, harvests and consumer demand are calculated based on the stock levels of each period. To account for this the economic parameters of the model are calibrated to harvests and prices of each period simultaneously. A detailed description of the calibration method is provided in Appendix 5.B.

Tables 5.1 and 5.2 present the calibrated and output values of the model elements in steady-sate. Figure 5.2 shows the output of the calibration for SSB (stock), harvest, and prices. The predicted values for SSB resemble the real tendency of the stocks during the last forty-five years. The harvest predictions of plaice before the TAC was introduced are higher than the real time-series. This is because the modelled fleet adjusts automatically to the new levels of stocks and prices, while in reality, the enter-exit movement of the firms occurs over a longer time frame. The predicted values of plaice show a decreasing price from 1982 to 1986 followed by a decreasing harvest. After the introduction of the plaice box in 1989 the plaice price increased together with plaice harvest until the TAC becomes binding in 1995. The predicted values of sole harvest follow the binding TAC. Since 1987 the predicted sole price starts increasing followed by a slight increase in harvest until 1999 when the TAC decreases again. For the last ten years, the predicted sole harvest and prices resemble the real values. However, the predicted plaice harvest follows the path of the TAC because the real fishing capacity do not keep up with the TAC and the plaice industry do not profit much from it since the plaice price is low.

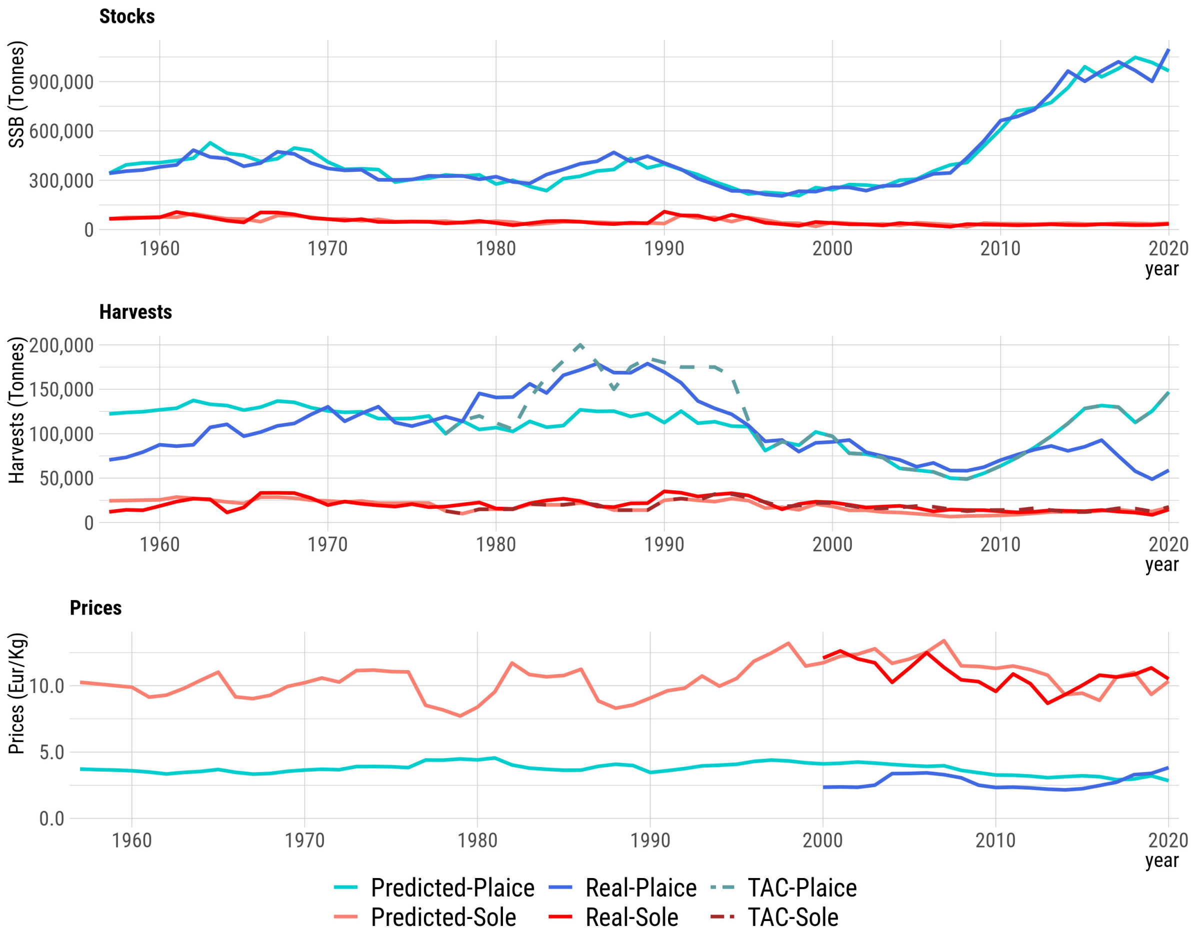

Figure 5.2: The difference between the real data and predicted levels of stocks (top), harvests (centre), and prices (bottom). Predicted stock levels are the result of predicted growth, given the real data in the previous period. The shown predicted levels of harvests and prices are based on the real stock levels of each period. Theil Inequality Coefficient: Stocks: Plaice = 0.049, Sole = 0.1507 Harvest: Plaice = 0.1506, Sole = 0.1389 Prices: Plaice = 0.1615, Sole = 0.0516

5.4.3 Application of The Analytical Framework to the Bio-Economic Model

The vulnerability framework presented above enables us to find the vulnerabilities of many system properties to many drivers. Hence, the main question to answer before proceeding with the case study is the vulnerability *of* what *to* what?. We select fishers' economic viability to answer the first "what" as the most critical aspect in this sector (Schuhbauer and Sumaila, 2016). For the second "what" we assess drivers derived from changes in ecosystem, harvesting process, market, and household preferences (θ).

In our application, we replace $\psi(\theta)$ by $\pi(\theta)$, which corresponds to the fishers' profits. There are two fishers' métiers ($k \in \{1,2\}$) that fish two species ($i \in \{1,2\}$). We evaluate profits of two metiers, hence $\pi(\theta) = (\pi_1(\theta), \pi_2(\theta))$. Profits are a function of the set of

Symbol	Value	Description	Exposure	
Ecosystem drivers			Absolute (Min, Max)	Percentage (Min, Max)
x_i	$x_1 = 148.589$ $x_2 = 85.936$	Steady-state output for stocks of plaice and sole in tonnes.	$x_1 : 69.472, 372.642$ $x_2 : 30.555, 186.961$	$x_1 : -53\%, +150\%$ $x_2 : -64\%, +117\%$
Harvesting drivers				
ϵ	0.5	Returns to effort. A higher value of ϵ refers to lower returns per unit of effort, while $\epsilon < 1$.	0.48, 0.52	$-3.09\%, +4.26\%$
χ_i	$\chi_1 = 0.308$ $\chi_2 = 0.308$	Stock harvesting efficiency of the species i. Represents the ability to catch a species depending on stocks availability (catchability).	$\chi_1 : 0.093, 0.607$ $\chi_2 : 0.230, 0.549$	$\chi_1 : -69, 7\%, +96.8\%$ $\chi_2 : -25, 2\%, +78.0\%$
$\nu_{ik}^{\ddagger}$	$\nu_{11} = 1.00$ $\nu_{12} = 0.75$ $\nu_{21} = 0.00$ $\nu_{22} = 0.25$	Métier specific harvesting efficiency (ν_{ik}) of the species i targeted with the métier k.	$\nu_{12} : 0.957, 1.052$ $\nu_{12} : 0.435, 1.014$ $\nu_{21} : 0.000, 0.000$ $\nu_{22} : 0.168, 0.324$	$\nu_{11} : -0.4\%, +5.2\%$ $\nu_{12} : -42\%, +35.2\%$ $\nu_{21} : -0.0\%, +0.0\%$ $\nu_{22} : -32\%, +29.9\%$
Market drivers				
p_i	$p_1 = 5.6$ $p_2 = 6.6$	Market prices in (Euros/Kg) for plaice p_1 and sole p_2 in steady-state.	$p_1 : 4.36, 7.77$ $p_2 : 5.31, 7.73$	$p_1 : -22\%, +38.6\%$ $p_2 : -20\%, +16.0\%$
$\omega^{\ddagger}$	1	Wages. The model wage is normalized to one, and households receive a unit to spend in either other goods or fish.	0.65,1.37	$-35\%, +37\%$
ϕ	1.0 x10^{-8}	Fixed costs of harvesting firms. Costs of owning the harvesting vessel and equipment independent of use.	8.3 x10^{-9}, 1.4 x10^{-8}	$-17\%, +40\%$
Household preferences drivers				
α	6.77 x 10^{-5}	Relative importance of fish consumption for households.	5 x 10^{-5}, 3 x 10^{17}	$-26.0\%, +\infty$
β_i	$\beta_1 = 2.69$ $\beta_2 = 4.14$	Weight of the species i in the household utility function.	β_1 : 0.1, 6 x 10^{12} β_2 : 1 x 10^{-6},6 x 10^{6}	$\beta_1 : -96\%, +\infty$ $\beta_2 : -99\%, +\infty$
η	1.10	Elasticity of demand for fish consumption.	0.001, 199	$-99\%, +\infty$
σ	2.01	Substitution elasticity between plaice and sole.	1.61, 3697	$-20\%, +\infty$

Table 5.1: Calibration results for each parameter, and steady-state values for prices, and stocks. ‡These parameters are not included in the calibration and are taken from the theoretical results in Blanz (2019).

Symbol	Value	Description
Steady state values		
n_i	$n_1 = 383$, $n_2 = 2315$	Optimal number of firms for each species.
h_{ik}	$h_{11} = 13.752$, $h_{12} = 62.317$, $h_{21} = 0.00$, $h_{22} = 17.545$	Optimal harvests (h_{ik}) of species i per metiér k in tonnes. The fleet targeting plaice ($k = 1$), only catches plaice.
e_k^*	$e_1 = 1.0$x10^{-8}, $e_2 = 1.0$x10^{-8}	Optimal effort in steady-state for the metiér k. This is the effort that results from the zero profit condition and profit maximization(Eq. 5.42).
Scaling parameters		
κ	$533.459, 8$	Scaling parameter for stocks. The real values of SSB and landings were divided by this parameter to scale to model values.
$wScale$	10.052.180x10^{6}	Scaling parameter for the income of the economy. This value correspond to the whole economy GDP of the North Sea countries for the year 2015.

Table 5.2: Calibration results for steady-state values of firms, harvests and effort. κ and $wScale$ are used to scale the real data to model values.

drivers (θ) and depend on harvests (h_{ik}) of species i with métier k, prices (p_i) of species i, effort (e_k) of the métier k, wages (ω), and fixed costs (ϕ) (Eq. 5.17). We analyse profits before the 'zero profit condition' holds to allow profits to deviate from zero (Eq. 5.34). We investigate the short term effects on individual fishing companies. Market forces will drive profits to zero by entries and exits of firms in the long term. Our analysis precedes these adjustments. I.e., if profits are likely to decrease/increase due to changes in a driver, this forms the incentives for firms to enter or exit the market in the longer term. In our case study we replace the adaptation mechanism $\tau_m(\theta)$ by effort $e_k^{**}(\theta)$ [4]. The modelled fisher adapts to changed conditions by modifying fishing effort (Eq. 5.19). We name (e_k^{**}) the adaptive effort to distinguish from the equilibrium effort ($e_k^*(\theta)$) which is derived once the zero profit condition holds (Eq. 5.42).

$$\pi_k(\theta) = \sum_{i=1}^{\bar{i}} h_{ik}(e_k^{**}, x_i)p_i - \omega e_k^{**} - \phi \tag{5.17}$$

In Eq. 5.17 harvest (h_{ik}) and adaptive effort (e_k^{**}) are defined in Eq. (5.18, 5.19) where x_i is the available stock, ν_{ik} is the métier harvesting efficiency, χ_i the stock harvesting efficiency, and ϵ the returns to effort.

$$h_{ik}(e_k^{**}, x_i) = \nu_{ik}(e_k^{**})^{\epsilon} x_i^{\chi_i} \tag{5.18}$$

$$e_k^{**}(\theta) = \left(\frac{\epsilon}{\omega} \sum_{i=1}^{\bar{i}} \nu_{ik} x_i^{\chi_i} p_i) \right)^{\frac{1}{1-\epsilon}} \tag{5.19}$$

Drivers

We consider drivers that emulate actual changes affecting fishers' profits. For example, an entry fee for fishing in certain areas changes fixed costs (ϕ), changes in harvesting technology modify the métier harvesting efficiencies (ν_{ik}), or changes in environmental factors alter the available stock (x_i). Regarding household preferences, a national campaign that encourage/dissuade fish consumption changes the importance of fish for consumers (α). An incentive for consumption of one species alters the elasticity of substitution (σ), or the weight of species in the utility function (β_i). The drivers evaluated further include wages (ω), where all variable costs are embedded, returns to effort (ϵ), stock harvesting efficiencies (χ_i), elasticity of fish consumption (η), and prices (p_i). The vector containing all drivers is given by $\theta = (\omega\ \phi\ \nu_{11}\ \nu_{12}\ \nu_{21}\ \nu_{22}\ \epsilon\ \chi_1\ \chi_2\ \sigma\ \alpha\ \beta_1\ \beta_2\ \eta\ p_1\ p_2\ x_1\ x_2)$. θ_j corresponds to a single driver for a total of $J = 18$ drivers evaluated.

[4] In our application we evaluate two properties $K = 2$ and use two adaptation behaviours for each property that correspond to the effort of each métier ($K = 2$), hence we use the same index k for both. Note that our framework allows multiple adaptation mechanisms for one system property, but in this application we use only one.

Exposures

Exposure is defined as changes in values for each element of θ (Eq. 5.2). The magnitude of exposure for each driver is based on historical variations of harvests, stocks, prices, wages, and fixed costs observed in the data. We use the harvest variations to identify the exposure limits for the métier harvesting efficiency (ν_{ik}), returns to effort (ϵ), and stock harvesting efficiency (χ_i). Using Eq. (5.18) we obtain the maximum and minimum intervals of each driver that result in the same harvesting range. Exposure levels of stocks (x_i), prices (p_i), wages (ω) and fixed costs (ϕ) are taken from maximum variations in the data [5]. We use the values of the North Sea countries with the maximum deviations as a reference for exposures. For the household drivers (σ, α, β_i, and η), the boundaries match the upper and lower bounds reflected in the harvest intervals using Eq. (5.22). The selected exposures for each driver are described in the last column of Table 5.1. They are interpreted relative to the steady-state values, i.e., the status-quo of the system from which the vulnerabilities are analysed.

Sensitivities

We characterize the sensitivities of fishers' profits to drivers from the ecological, harvesting, market, and household components (Table 5.1). Sensitivities are described using Eq. (5.3). We analyse individual sensitivities of profits for each driver, holding other drivers constant. An example of the absolute sensitivity of profits to changes in stock harvesting efficiency (χ_i) is Eq. (5.21). χ_i is the new level of exposure and ${}^0\chi_i$ the original value, keeping stock and prices constant at steady-state levels. We apply the same exercise for ecosystem, harvesting, and market drivers. For stock changes (x_i) prices are constant, and for changes in prices (p_i), stock is constant.

$$S_k(\theta, {}^0\theta) = \pi_k(\theta, e_k^{**}({}^0\theta)) - \pi_k({}^0\theta, e_k^{**}({}^0\theta))$$

$$\theta = (0, \ldots, \chi_i, \ldots, 0) \tag{5.20}$$

$${}^0\theta = (0, \ldots, {}^0\chi_i, \ldots, 0) \tag{5.21}$$

[5] The sample of maximum and minimum variations are within the 95% of confidence intervals.

We use Eq. (5.22) to find the sensitivities of profits to household drivers. This equation is derived from the household optimization procedure and represents the demand for one good given the consumption of the other. Profits are affected by household drivers through the demand side, i.e., changes in these drivers affect the quantity demanded, then the effort is adjusted to this new quantity and later profits change. In our analysis the market clearing condition holds, i.e., harvest is equal to the demanded quantities (Eq. 5.39). The optimal prices (p_i) and demand (q_{-i}) at steady-state are held constant for the analysis not to muddle effects. We follow Eq. (5.21) to find the absolute sensitivities from the household component.

$$H_2 = q_2 = \left(\left(\frac{p_1}{\alpha\beta_1} (\beta_1 q_1)^{\frac{1}{\sigma}} \right)^{\frac{\eta(\sigma-1)}{\eta-\sigma}} - (\beta_1 q_1)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} (\beta_2)^{-1} \tag{5.22}$$

The sensitivities of profits to a marginal change in drivers are defined by Eq. (5.23). Profits are evaluated with the adaptive effort (e_k^{**}) embedded, not the equilibrium effort (e_k^{*}), hence this derivative is different than zero.

$$s_{kj}(\theta) = \frac{\partial \pi_k(\theta, e_k^{**}(^0\theta))}{\partial \theta_j} \tag{5.23}$$

Adaptive Capacities

We determine the adaptive capacities by evaluating the difference in profits in two cases. We elicit profits when fishers first experience the change in the driver $\pi_k(\theta, e_k^{**}(^0\theta))$, without yet modifying their effort. Then, we identify profits after adaptation $\pi_k(\theta, e_k^{**}(\theta))$, once the effort is adjusted to the new level of the driver $e_k^{**}(\theta)$. The difference in profits between these two values yields the absolute adaptation equation per métier k for each driver (θ_j). We assess individual adaptive capacities for each driver θ_j holding others constant following the same procedure as with the sensitivities.

$${}^{a}A_k(\theta, {}^0\theta) = \pi_k(\theta, e_k^{**}(\theta)) - \pi_k(\theta, e_k^{**}(^0\theta)) \tag{5.24}$$

The marginal adaptation measures for fishers' profits using the adaptation effort with métier k to the driver j are in Eq. (5.25. 5.26, 5.25). Eq. (5.24,5.25) evaluated at steady state (${}^0\theta$) are zero. In our framework adaptation is always positive, i.e., it is increasing with any deviation from zero exposure, consequently the derivative is zero at this point.

$$ {}^a a_{kj}(\theta) = \frac{A_k(\theta, {}^0\theta)}{\partial\, \theta_j} \tag{5.25} $$

$$ {}^b a_{kj}(\theta) = \frac{\partial^2 A_k(\theta, {}^0\theta)}{\partial^2\, \theta_j^2} \tag{5.26} $$

$$ {}^c a_{kj}(\theta) = \frac{\partial e_k^{**}(\theta)}{\partial\, \theta_j} \tag{5.27} $$

Vulnerabilities

We use Eq. 5.14 to derive vulnerabilities of profits to multiple drivers. Vulnerabilities are determined as the overall difference in profits at the initial level of the driver (${}^0\theta_j$) and at the new level (θ_j). Profits at the initial level of the driver and without adaptation yield: $\pi_k({}^0\theta_j, e_k^{**}({}^0\theta_j))$. Profits at the new level of the driver and with adaptation included yield: $\pi_k(\theta_j, e_k^{**}(\theta_j))$. We assess the vulnerabilities using Eq. (5.28), for each driver independently.

$$ V_k(\theta, {}^0\theta) = \pi_k(\theta, e_k^{**}(\theta)) - \pi_k({}^0\theta, e_k^{**}({}^0\theta) \tag{5.28} $$

The marginal vulnerabilities contemplate the derivative of profits once there is an optimal adaptation to the change in the driver (Eq. 5.29).

$$ v_{kj}(\theta_j) = \frac{\partial V_k(\theta, {}^0\theta)}{\partial\, \theta_j} \tag{5.29} $$

5.5 Results

In our case study we investigated the sensitivity, adaptive capacity, and vulnerability *of* fishing profits in the two métiers targeting plaice and sole in the North Sea *to* a wide range of drivers. The vulnerabilities, adaptive capacities, and sensitivities of profits to drivers are presented in Figure 5.5 for the plaice fleet and Figure 5.6 for the sole fleet.

The horizontal axes represent the magnitude of exposure for each driver (θ_j) within the levels established in Table 5.1. The change in profits on the vertical axes is calculated relative to steady-state profits. Profits are scaled relative to the household income (ω). As exposures are relative to the starting value, the initial level of exposure, adaptation, sensitivity, and vulnerability is zero.

The profits of these fleets are influenced by drivers affecting the ecological system, the harvesting process, the market, and household preferences. We abstracted from the ecological causes of stock change by investigating changes in the stock level itself (x_i). Figure 5.5.a shows increasing profits with stocks, causing a positive slope in the sensitivity. By adjusting effort to the new levels of stocks profits increase (Eq. 5.18). Figure (5.10) shows that a marginal increase in plaice stock increases adaptive effort. The increased effort raises costs and revenue, but the latter outweighs costs so that profits increase generating positive vulnerability. The opposite effect occurs when stocks decrease, costs are mitigated by reducing the adaptive effort and the negative sensitivity is reduced. Figure 5.5.b shows no vulnerability of plaice fishers to changes in sole stocks (x_2), as they do not harvest sole.

The harvesting process is affected by changes in returns to effort (ϵ), stock harvesting efficiency (χ_i) and gear harvesting efficiency (ν_{ik}), which in turn are influenced by policy. ϵ, for instance, changes by policies establishing marine protected areas (MPAs) or wind farms, so that the fishers' effort (time at sea) to obtain a certain amount of harvest changes (ϵ). A policy reducing the harvesting efficiency corresponds to an increase in epsilon. Figure 5.3.a shows that a higher value of ϵ leads to lower returns to effort. This is a result of normalising the total labour pool to unity and consequently effort being lower than one. An increase in ϵ decreases the effective effort (e_k^{ϵ}), consequently decreasing harvest resulting in lower profits (Fig. 5.3). The adaptive capacity (e_k^{**}) decreases with ϵ reducing the fishing costs and, hence, counteracting the sensitivity (Fig. 5.5.c). Changes in the availability of stocks modify χ_i. The analysis for χ_i resembles the reasoning of ϵ (Fig. 5.5.d). A higher χ_i represents a decrease in the ability to harvest due to less available stocks. Lastly, changes in gear restrictions such as bans of pulse trawling change ν_{ik}. A marginal increase in ν_{ik} increases adaptive effort (Fig. 5.10) and has a positive relation with profits (Fig. 5.5.f).

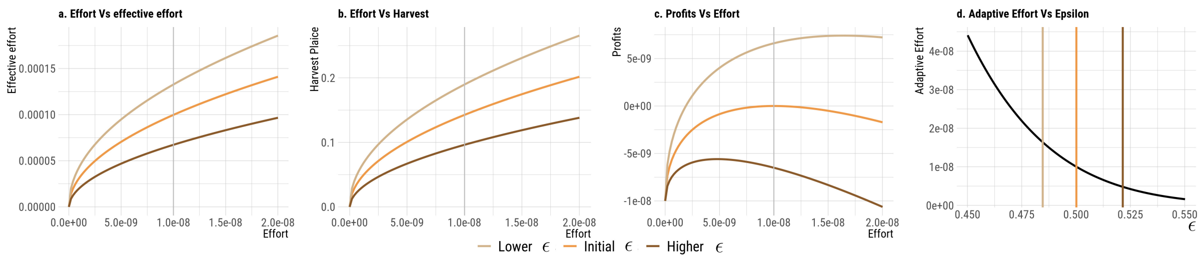

Figure 5.3: Cascading effects among sub-systems due to changes in returns to effort (ϵ). Higher ϵ represents lower returns to effort. Figure a. shows the relationship between effort (e) and effective effort (e_k^{ϵ}) for a lower, initial and higher ϵ. Figure b. shows the effort vs harvest for each level of ϵ. Figure c. presents the profits for each level of effort presented in b. Note that at an initial ϵ maximum profits are zero, i.e., at steady state. Figure d. describes the adaptive capacity (e^{**}) and ϵ. The vertical grey line represents the initial value of effort in steady state.

The drivers affecting the fish market include prices (p_i), wages (ω) and fixed costs (ϕ), these can be affected by policies such as establishing subsidies or taxes. Prices affect profits in a similar way to stocks (Eq. 5.17). Contrarily, a decrease in wages reduces costs per unit of effort, thus increasing the adaptive effort. Both aspects combined generate higher adaptation to a decrease than to an increase in wages (Fig. 5.5.i). Finally, fishers' adaptive capacity to changes in fixed costs (ϕ) is zero, as we only investigate adaptation through effort that have no bearing on ϕ (Fig. 5.5.j).

The last row of Figure 5.5 shows the impact of household preference drivers on profits. In our application changes in these drivers affect profits through demand. Policies affecting these drivers include campaigns to promote/ discourage consumption of fish. An increase in the importance of fish consumption (α) has no effect on profits, hence vulnerability is zero (Fig. 5.5.k). A higher α increases demand, but effort remains constant because increasing capacity, such as new vessels, requires higher costs in the short term. If effort increases costs exceed revenues, therefore fishers adapt by keeping the same effort level (Fig. 5.4). Contrarily, a decrease in α reduces demand and revenue. Hence, decreasing adaptive effort lowers costs counteracting the sensitivity (Fig. 5.4.d). A similar analysis applies for the weight of species in household utility (β_i), elasticity of fish consumption (η), and elasticity of substitution (σ). β_2 shows the opposite effect of β_1, since plaice and sole are supplementary goods. Finally, the impact of drivers on the sole fleet is similar to those of the plaice fleet (Fig. 5.6).

Next, we compare the overall impact of each driver on fishers' profits for the extremes of the exposures considered (Fig. 5.7). The drivers with the largest impact are plaice

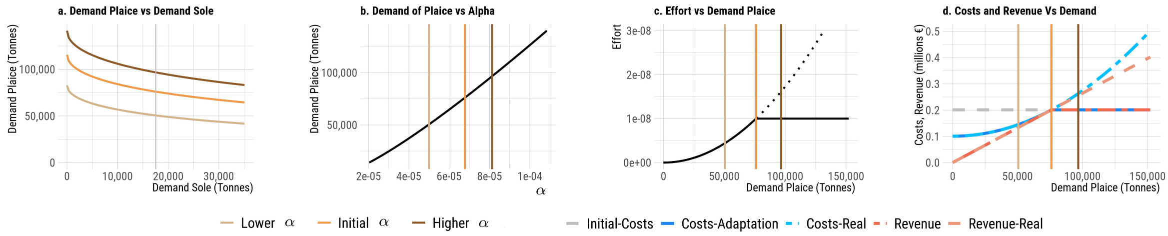

Figure 5.4: Cascading effects among sub-systems due to changes in α. Higher α represents more importance of fish consumption for households. Figure a. shows the changes of plaice demand for a given sole demand in a set of lower, initial and higher α (Eq. 5.22). Figure b. presents the changes in plaice demand vs α. Figure c. indicates the adjusted effort for a change in plaice demand. The dotted line represents the possible increase in effort if firms could easily adapt in response to an immediate increase in demand. Figure d. displays costs and revenue for demanded quantity plaice. Costs-Real and Revenue-Real are probable scenario if fishers could increase their effort immediately. The grey dashed line represents the initial costs without effort adaptation, and Costs-Adaptation includes adaption.

prices (p_1), returns to effort (ϵ), stock harvesting efficiency of plaice (χ_1), plaice stocks (x_1) and wages (ω). The price (p_1) and stock of plaice (x_1) significantly impact profits in both absolute and marginal terms. The higher proportion of plaice in the fleets' harvest generates a greater impact of these species on profits (Table 5.2). The high impact of ϵ on profits is due to the strong effect on adaptive effort (Figure 5.10). The wider levels of exposure considered for ω and χ_1 generates a high impact on profits.

Our results allow us to determine the drivers to which fisheries adapt the best. Figure 5.7 shows the fishers' effort adaptation to positive and negative exposures. Fishers best adapt to the weight of species in utility (β_i) and a decrease in wages (ω). A decrease in β_1 has a large reduction on profits as plaice is the most harvested species. To counteract the decline in profits the adaptive effort decreases also in a wider range reducing costs (similarly for β_2). The modelled fishers also present a higher adaptive capacity to changes in wages than any other driver, especially when they decrease. Lower wages allow fishers to maintain the same effort at lower costs or even increase their effort. For most drivers, plaice fishers are more vulnerable than sole fishers. The latter have more diversified income provided by the simultaneous catching of both species.

Figure 5.8 shows the marginal sensitivities of profits. Profits are mostly sensitive to changes in ϕ, ϵ, p_i, and α. Fishers' profits are also more affected by a marginal change in prices than stocks. The marginal vulnerability described by Eq. (5.29) in steady state is equal to the sensitivity for the ecosystem, harvesting and market drivers. For the household drivers the marginal vulnerability is zero for metier 1. For metier 2

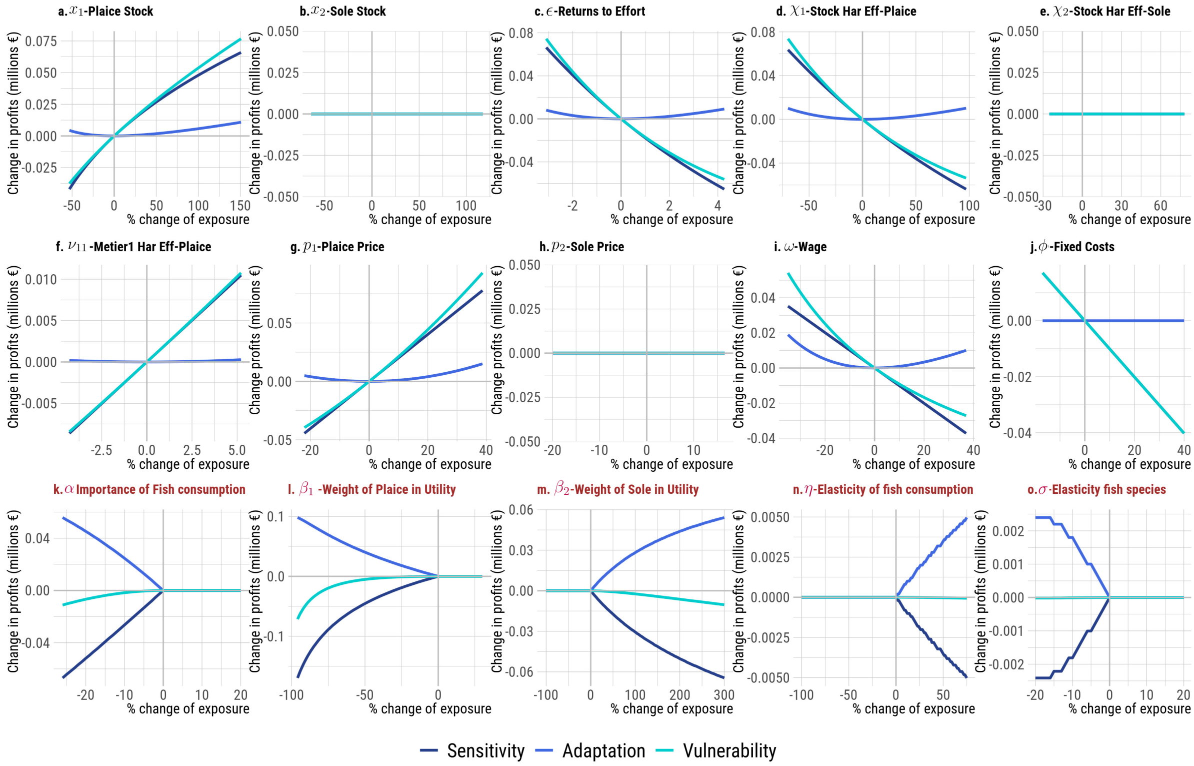

Figure 5.5: Adaptation, sensitivity and vulnerability of plaice fishers' profits to multiple drivers for the plaice métier. The horizontal axes show the increase and decrease of exposure from the steady state (relative to ${}^0\theta$. The vulnerabilities for the métier specific harvesting efficiency of sole targeted with métier 1 (ν_{21}) are zero and are not presented since this métier does not target sole.

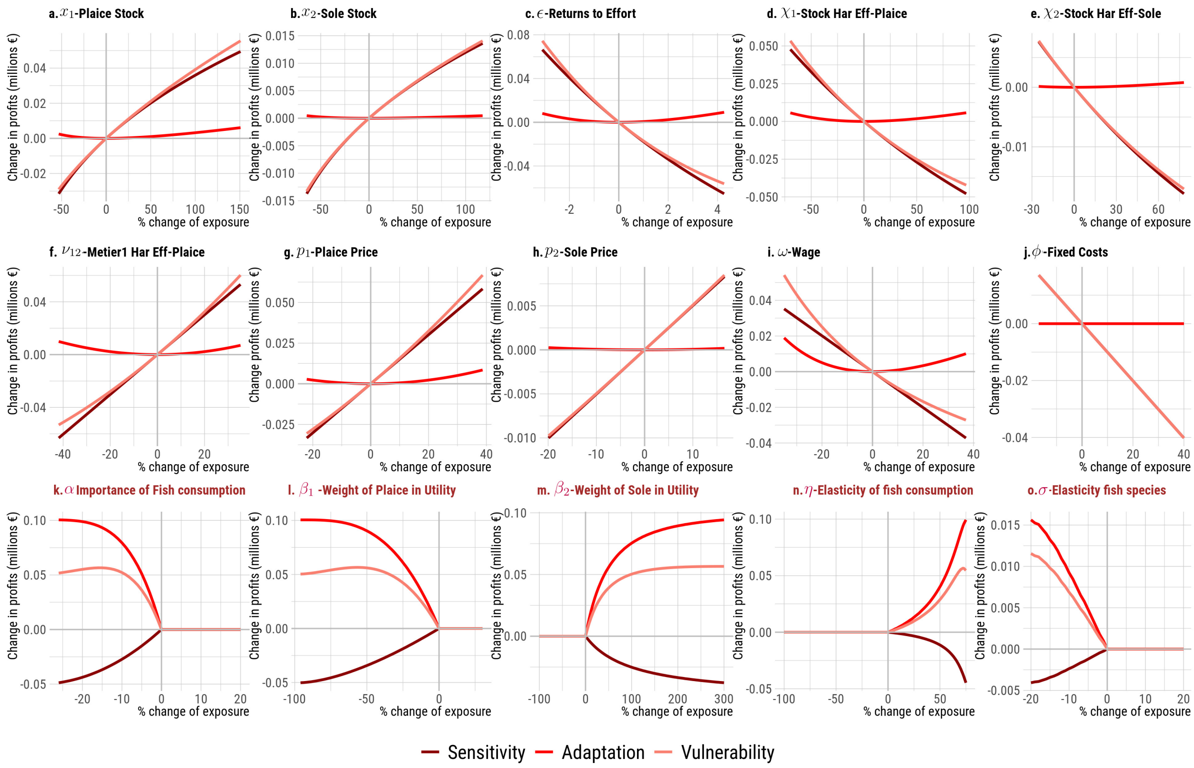

Figure 5.6: Adaptation, sensitivity and vulnerability of sole fishers' profits to multiple drivers for the sole métier. The horizontal axes show the increase and decrease of exposure from the steady state in percentage points (pp).The vulnerabilities for the métier specific harvesting efficiency of sole targeted with métier 2 (ν_{22}) have the same structure of the ν_{12}.

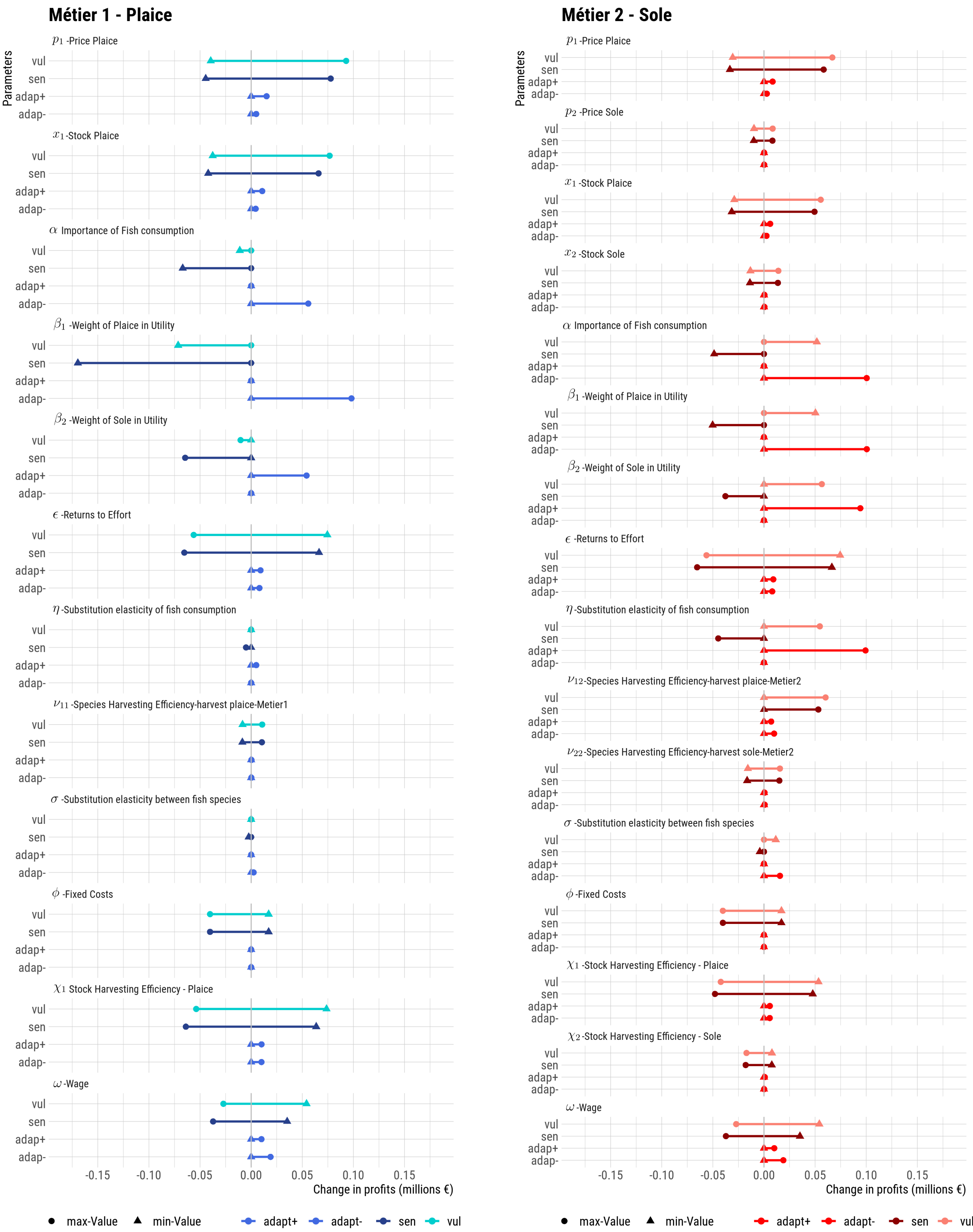

Figure 5.7: Impact on fishers profits to changes in all drivers. The horizontal axis shows the minimum and maximum vertical values of profits presented in figure 5.5 and 5.6. 'adapt+' represents the effect of adaptation on changes in profits when exposure increases, and 'adapt-' when exposure decreases. The symbols represent the maximum and minimum value of each driver. Fixed costs have the highest impact on profits. These are not plotted to show a clearer perspective of others drivers.

the importance of fish consumption (α) has the highest marginal effect on profits, once adaptation is performed, in comparison to other household drivers.

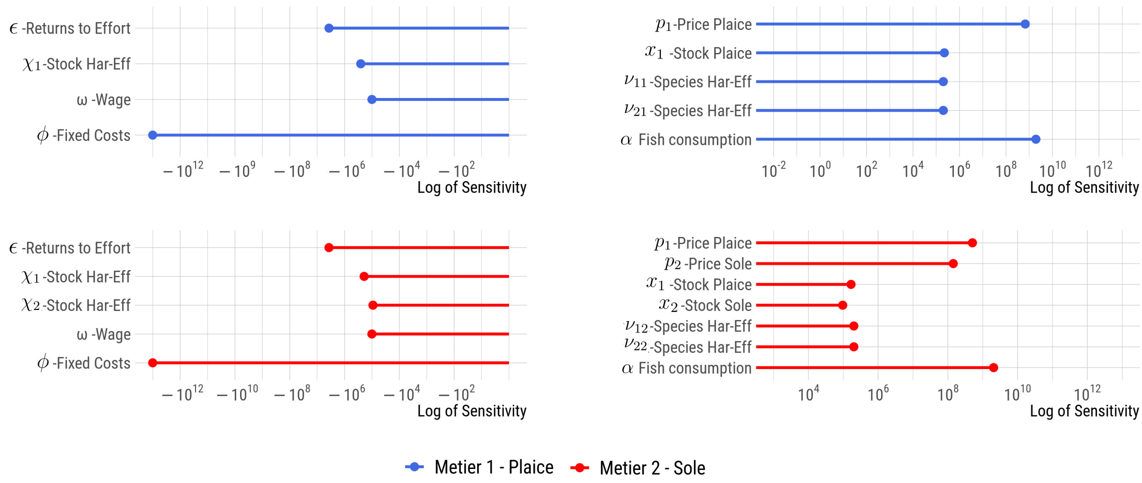

Figure 5.8: Marginal sensitivity of profits to changes in drivers. The horizontal axes represent the marginal sensitivities in log form. Drivers that are not presented here have no impact on profits.

The marginal adaptive capacities ${}^{a}a_{kj}(\theta)$ in steady state ${}^{0}\theta$ are zero for all drivers (See Fig. 5.5 and 5.6). Hence, we present ${}^{b}a_{kj}(\theta)$ and ${}^{c}a_{k}(\theta)$ in figures 5.9 and 5.10 respectively. The second derivative in steady state of the adaptive capacity shows the rate at which profits change by a modified effort with a change in the driver. Fig 5.9 shows that the change in profits by modified effort changes the most for marginal changes in the importance of fish consumption (α), prices (p_i) and returns to effort (ϵ) for both métiers. Finally, ${}^{c}a_{k}(\theta)$ shows the change in adaptive effort given by a marginal change in the driver (Eq. 5.27). The adaptive effort is mostly affected by returns to effort (ϵ) followed by plaice price (p_1) and importance of fish consumption (α). Additional results for adaptation measures in points different than steady state are presented in appendix 5.C.

The absolute and marginal measures of vulnerabilities complement each other. Absolute values depend on the level of exposure, and evaluate adaptation and effects on profits regarding abrupt changes in drivers. Marginal measures show the effect of marginal changes in drivers and are independent of the level of exposure. This is useful where the level of exposure is uncertain. The marginal measures correspond to the slope of the respective absolute measures. Marginals also provide an overview of trade-offs among drivers' effects on profits and adaptive capacity.

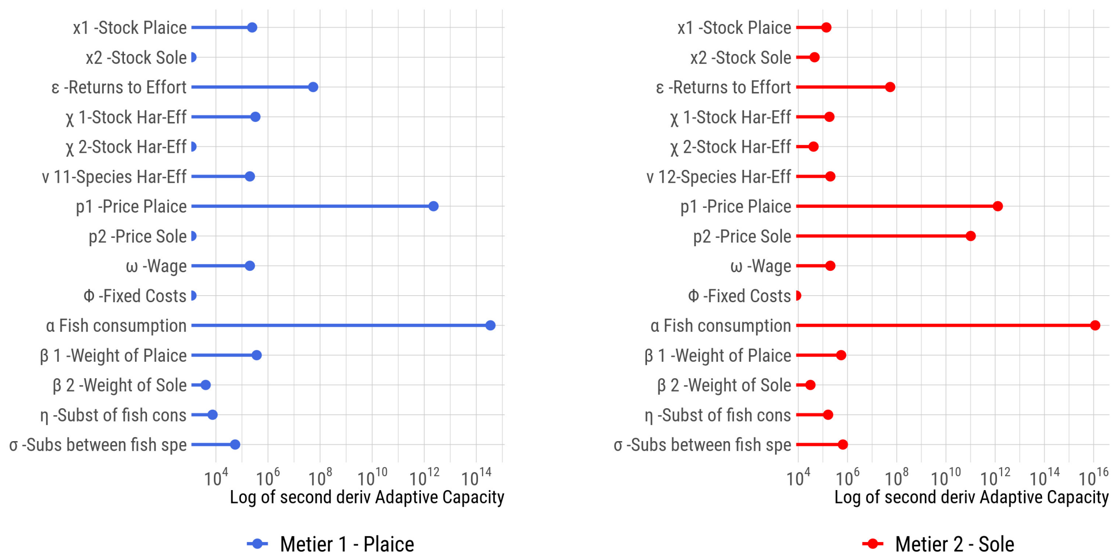

Figure 5.9: Marginal adaptive Capacity ${}^{b}a_{kj}({}^{0}\theta)$ of profits to changes in drivers. The horizontal axes represent the marginal adaptive capacities in log form. Drivers that are not presented here have no impact on profits.

5.6 Discussion

In our results major factors affecting fishers' profits are the plaice price, returns to effort, and fixed costs. In the North Sea, the plaice price plays an important role in total revenue (Scientific , technical and economic committee for fisheries (STECF)., 2021). In this region, the price is largely determined by fish processing organisations in The Netherlands, the largest producer of European plaice worldwide (European Commission, 2016). Therefore, the investigated small-scale fishers have no control over the price. Fishers also experienced changes in returns to effort resulting from increasing coverage of MPAs (Russi et al., 2016), the current development of wind farms (Stelzenmüller et al., 2020), and shifts in species distribution (Engelhard et al., 2011). These aspects increase the time at sea, making the fishing process less efficient. Fixed costs also substantially fluctuated ranging from 16% and 49% between 2008 and 2018 among all North Sea countries (Scientific , technical and economic committee for fisheries (STECF)., 2021). These costs are strongly influenced by vessel size and age (Lam et al., 2011). Since the number of vessels is decreasing for this fishery, fixed costs might continue reducing fishers' profits in the next years. The application of our framework shows how these changes affect fishers prof-

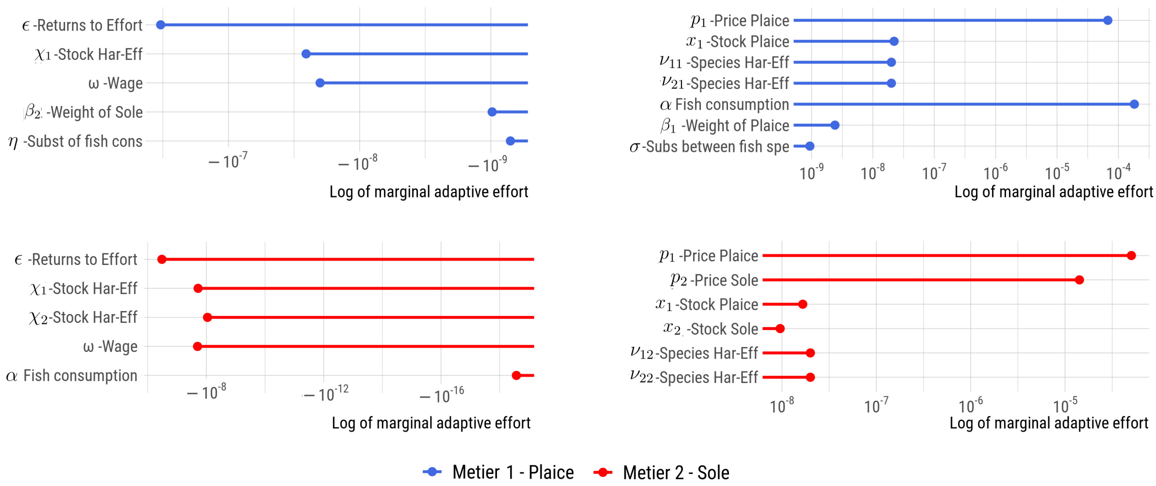

Figure 5.10: Marginal adaptive capacity. Change of adaptive effort to marginal changes in drivers. The horizontal axes represent the marginal adaptations in log form. Drivers that are not presented here have no impact on effort.

itability and to what extend the internal adaptive capacity of the fisheries can mitigate these effects.

We also address climate drivers derived from changes in stocks. We evaluate changes in stocks within the historical range, however, future climate change might move stocks outside of this range, including the risk of depletion. We show that if stocks changes stay within the historical range they affect profits proportionally less than prices, returns to effort, or fixed costs. In the case of plaice even if stocks decline slightly profits remain unchanged, as the TAC has not been fully exploited.

Our framework allows differentiating between the effects of various drivers on profits. For instance, if the aim of the decision-maker is increasing fishers' profits, we show that the huge negative impact of increasing returns to effort on profits can be off-set by reducing fixed costs. The latter is critical since our modelled fisheries cannot adapt to fixed costs by changing their effort. Since fixed costs have increased in this fishery it becomes challenging to establish policies to improve fishers' profits. Prosperi et al. (2019) mentioned that strategies such as reorganizing the supply chain or generating diversification help fisheries counteract increasing costs. Our framework also shows trade-offs among fishers' adaptive capacity to ecological/economic drivers. A decrease in prices requires stronger reduction in adaptive effort than a decrease in stocks. A less adaptive effort may translates into reduced employment in this sector. Hence, it is important to balance socio-economic and ecological aspects.

In 2019 this fishery experienced a sharp decrease (-18%) in employment compared to 2018 (Scientific , technical and economic committee for fisheries (STECF)., 2021). This could be the result of adaptation to simultaneous stressors, such as stocks moving towards another region, increasing fixed costs, shrink in active vessels, and reduced harvesting efficiency. The EU common fisheries policy (CFP), which covers the North Sea, is focused on ecological sustainability, while economic and social aspects remain secondary (Goti-Aralucea et al., 2018). Stock protection, although necessary, has consequences on society, and actions to mitigate adverse effects should be implemented, if the fishery is to remain. While it is true that fisheries can not exist without sustainable stocks, including measures to compensate the fishers' lost of income is an alternative. Goti-Aralucea et al. (2018) state that management measures that meet ecological, economical, and social objectives should be promoted, so that employment and livelihoods of fishers are ensured.

Our results also bring insights into adaptive capacities. Some studies assess adaptive capacities of the whole SES (Carpenter and Brock, 2008; Cottrell et al., 2020), and others of a social community embedded in the SES (Chen et al., 2020; Cabral et al., 2015; Cinner et al., 2013). When assessing adaptive capacities in most cases the unit of analysis is unclear, i.e., "the adaptive capacity of what to what?" (Whitney et al., 2017). Our framework answers this question for multiple drivers. We find that fishers have the highest adaptive capacity to changes in species preference, consumption, and wages. Our adaptive effort measure represents the full-time equivalent (FTE) units necessary to perform the fishing activity. It gives an indication of employment changes this adaptation would cause. Hence, while the adaptation may serve to safeguard fishers' profits it does not safeguard livelihoods. With the framework, this analysis can be performed by investigating the impacts of the drivers on effort, and employment.

Our results highlight the importance of household preferences on the SES. Bio-economic models are used to study the effect of the elasticity of substitution (Baumgärtner et al., 2011; Quaas et al., 2013), and consumers' subsistence requirements (Baumgärtner et al., 2017) on SESs. These models show the effects of consumer preferences on the SES, and highlight that these preferences are a determinant of the dynamics in the system (Baumgärtner et al., 2011). Our framework and case study add to this literature showing that with a calibrated bio-economic model it is possible to establish and compare the impacts of consumer preferences on harvests and profits. In our case study, we show

how changes in the preference of place consumption (β_1) affects profits more than other household drivers.

In our case study, we show an endogenous adaptation through effort, but the framework is not restricted to this adaptation path. By further investigating which drivers would be changed by preservation policies, our approach highlights one of the most likely unintended knock-on effects. In our framework, governance options are considered exogenous adaptation and are not yet embedded in our analysis. This constitutes one avenue for future research.

We analyse the impact on profits of multiple drivers from the ecological, economic, and social systems independently. Further research will analyse simultaneous impacts. SESs are frequently exposed to multiple changes at the same time. For instance, changes in political and ecological drivers can cause higher sensitivities than the sum of impacts separately. As such the analysis of these simultaneous impacts also has high policy relevance.

5.7 Conclusion

The multidisciplinary field of vulnerability has a variety of definitions and concepts, leading to confusion and imprecise policy advice. We develop a framework that clarifies and disentangles the concepts of vulnerability, sensitivity, and adaptive capacity using mathematical modelling. Our framework allows us to assess the vulnerabilities of multiple drivers to a system property, and to distinguish the benefits and harms of the drivers on the SES. Besides, it also identifies policy trade-offs among ecologic and socio-economic sub-systems.

We apply our framework to the North Sea flatfish fishery and investigate the vulnerability of fisheries profits to multiple drivers. Among the sixteen drivers evaluated we find that fishers' profits are most vulnerable to changes in plaice prices, returns to effort, stock harvesting efficiency of plaice, plaice stocks, and wages. We also find that a marginal increase in fixed costs strongly decreases profits and adaptive effort, making this driver an important factor to consider in management actions. As such, we provide insights of stressors and benefactors that need to be mitigated or heighten by policy measures to increase or maintain, fishers' profits. Specifically, the consequences that fishers' economic viability has on future changes in fleet size. Our results are relevant to decision-making, as they quantify the extent to which various drivers harm or enhance well-being in this fishery and to what extent the fishery can mitigate these effects endogenously. Our model also highlights the importance of household preferences in effort, harvests, and profits. This framework can be applied to other fisheries regions and be used with different bio-economic models. We consider that the generality of the definitions makes the application of our framework easy to implement.

5.A Model Description

We present a bio-economic model based on Blanz (2019). It provides us with tools to understand the North Sea fishery complexity. We add to this bio-economic model two main components. First, a variable that accounts for the weight of each species in the household' utility function (β_i). Second, the logistic growth function was replaced by the Ricker-recruitment function that, to our knowledge and data, provides a better fit to the stock growth for plaice and sole in the North Sea.

Figure 5.11 shows the components of the model. An ecosystem component describing the current state and dynamics, harvesting firms maximizing profits, and consumers maximizing contemporaneous utility. The market between the harvesting firms and households allows to sale harvested ecosystem stocks to consumers. The prices on this market and corresponding harvested quantities are determined endogenously. A second labor market allows firms to employ the labor provided by households in the harvesting or manufacturing of a numeraire commodity. Hence, it provides income to households to pay for the fish and other products consumed.

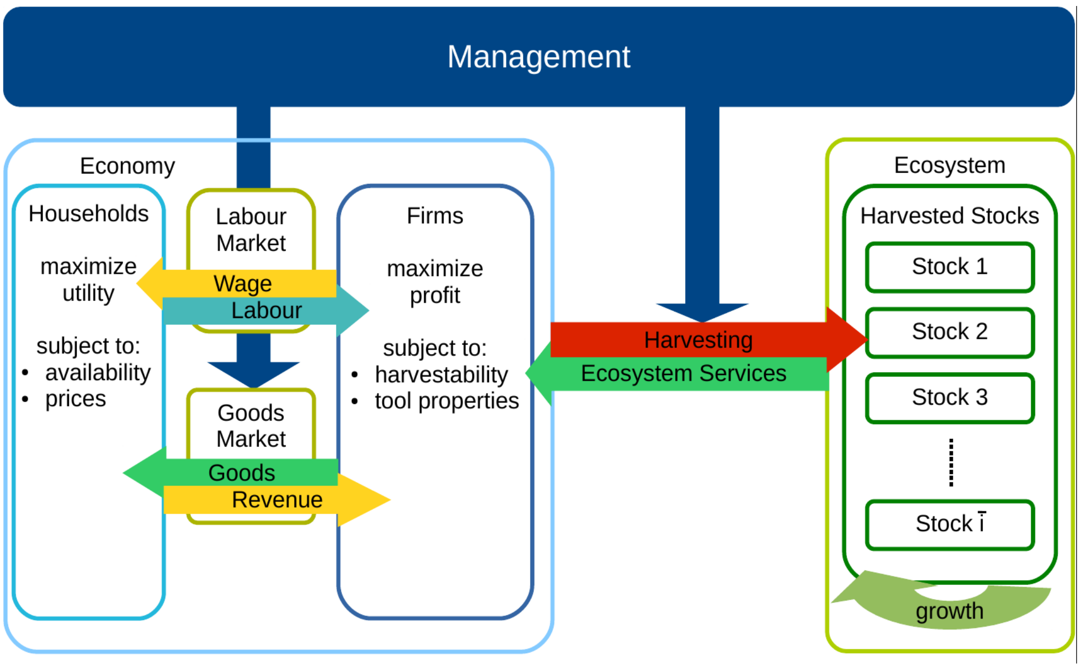

Figure 5.11: Components of the bio-economic model and their interactions

Ecosystem Properties

This sub-system is composed of $\bar{i}$ species. Stocks are denoted by x with indexes for species $i \in I$, where I is the set of all species $I = [1, i] \cap Z$. Species are assumed to grow each period t due to intrinsic growth g_{it} and are diminished by harvests H_{it}. This change in stocks is modeled by differential equations, determining the dynamics of the model. This is the only component of the model that account for time dependency.

$$\dot{x_{it}} = g_{it}(\mathbf{x}_t) - H_{it} \tag{5.30}$$

In equation 5.30 g_{it} is the biomass growth function represented by the Ricker-recruitment growth 5.31. It depends on the entire vector of stocks, and the parameters a_i and b_i. 'a_i' is density independent parameter proportional to fecundity and 'b_i' is a density-dependent parameter. If density-dependence in the stock-recruitment (growth) relationship does not exist, then $b = 0$.

$$g_i(\mathbf{x}) = a_i(x_i)e^{-b_i x_i} \tag{5.31}$$

Harvesting Properties:

Once the stock for each period is assessed, fisheries make their harvest choices based on the stock available x_i. The harvest component includes $\bar{k}$ mètiers, which encompasses all that is necessary for the fisher to harvest and is not dependent on the effort i.e. all upfront investments that are necessary to start operating.

Métiers are indexed by $k \in K$, where K is the set of all mètiers $K = [1, k] \cap Z$. Each métier has a target species, but may also catch other species, as by-catch. While individual firms may not change their métier, the economy-wide fleet size for each métier is dynamic. The change of gear in use occurs through the market entry and exit of firms performing different métier. where $\bar{i} = \bar{k}$.

Total harvest in the economy H_i of species i is determined by the number of firms n_k practicing métier k and the sum of the harvested quantity by each firm h_{ik} targeting the species i with métier k.

$$H_i = \sum_{k=1}^{\bar{k}} n_k h_{ik}(e_k, x_i) \tag{5.32}$$

The harvest per firm is defined following the generalized Gordon–Schaefer production function (Clark, 1990). Using the métier k the fisher can target the species i, but can also harvest other species. The fisher can not control the fish species that she catches. Therefore, the total amount of harvest H_i depends on the effort e_k practicing all the mètiers k capable of catching that species ($k \in K|\nu_{ik} > 0$). The effort experiences diminishing returns to effort ϵ and is determined under the assumption of perfect markets for harvesting goods and labor. The gear effect is governed by the gear matrix ν_{ik}. The elements of ν_{ik} specify the catchability for each species i by mètier k. Species abundance influences the harvest returns per effort through the harvestability function $\chi_i(x_i)$. It captures changes in harvest yield due to changing stocks. Less abundant species are more difficult to catch compared to species with high stock levels $\chi_i(x_i) = x_i^{\chi_i}$. In the following $\chi_i(x_i)$ will be abbreviated as χ_i. It specifies a square matrix containing the χ_i along the diagonal and zeros off the diagonal.

$$h_{ik}(e_k, x_i) = \nu_{ik} e_k^{\epsilon} \chi(x_i) \tag{5.33}$$

The profits of each firm are defined as the difference between income and costs. The income is derived from the quantity of fish harvested h_{ik} times the price of the species i, p_i. Costs include wages ω times the effort e_k, which is measured in units of labor, keeping the structure given by Quaas and Requate (2013). Fixed costs ϕ_k are defined per mètier k and represent fees for entering the markets, fixed price for quotas or also initial capital. In order to maximize profits each firm takes stock levels x_i, prices p_i and wages ω as given to define their effort e_k.

$$\max_{e_k} \pi_k = \sum_{i=1}^{\bar{i}} h_{ik}(e_k, x_i) p_i - \omega e_k - \phi_k \tag{5.34}$$

The maximization of these profits and the assumption of perfect markets leads the firms' profits to zero. Under an open-access scenario it derives to the optimal effort level, given by (5.42). Then, the firms' mètier specific equilibrium harvest is obtained from replacing e_k^* in the harvesting production function:

$$h_{ik}(x_i) = \nu_{ik} e_k^{*\epsilon} \chi(x_i) \tag{5.35}$$

Household Properties:

The household preferences involve the fish' consumers who have preferences for fish Q, and a numeraire commodity y. The utility is described by the function:

$$U(Q, y) = \begin{cases} y + \alpha \frac{\eta}{\eta-1} Q^{\frac{\eta-1}{\eta}} & \text{for } \eta \neq 1. \\ y + \alpha \ln Q & \text{for } \eta = 1. \end{cases} \tag{5.36}$$

The parameter η indicates the constant demand elasticity of fish, $\alpha \geq 0$ characterize the importance of fish consumption in overall consumption. Regarding the preferences over the fish species, they are modeled using a Dixit-Stiglitz utility function (Dixit and Stiglitz, 1977).

$$Q = Q(\mathbf{q}) = \left(\sum_{i=1}^{\bar{i}} (\beta_i q_i)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \tag{5.37}$$

In equation 5.37, q_i corresponds to the quantity of the fish species i consumed by the household. β_i represents the weight of each species in the utility function. This allows us to account for differences in demand quantity for a specific type of fish species. $\sigma > 0$ measures the elasticity of substituting between consumption levels of different species. Hence, perfect substitution is achieved when σ tends to infinity ($\sigma \to \infty$), and lower values illustrate the limited substitutability of fish species in consumption.

The households maximize their utility subject to the budget constrain. They allocate their wages ω received from providing labor to the fisheries and manufactured sector. The first part of ω is spent in a manufactured good y, which price is normalized to one. A second part is spent in fish, with the amount consumed q_i given the weight of each species in the utility function β_i and the price per species p_i.

$$\omega = y + \sum_{i=1}^{\bar{i}} (\beta_i q_i) p_i \tag{5.38}$$

To keep the analysis tractable, no savings or other capital accumulation is possible in the model. Additionally, Further to what is presented in Quaas and Requate (2013) and following Blanz (2019), household demand presents an additional restriction called the market-clearing condition. It states that whatever is harvested will be consumed for each species, such that the number of firms are non-negative $n_k \geq 0$

$$q_i = H_i = \sum_{k=1}^{\bar{k}} n_k h_{ik}(x_i) \tag{5.39}$$

Firm Optimization Problem

The firms maximize their profit and therefore find their optimal effort, resulting in the first order condition, from (5.34):

$$\frac{\delta \pi_k}{\delta e_k} = \epsilon \left(\sum_{i=1}^{\bar{i}} \nu_{ik} \chi(x_i) p_i \right) e_k^{\epsilon-1} - \omega = 0 \tag{5.40}$$

$$e_k^{**} = \left(\frac{\epsilon}{\omega} \sum_{i=1}^{\bar{i}} \nu_{ik} x_i^{\chi_i} p_i) \right)^{\frac{1}{1-\epsilon}} \tag{5.41}$$

Given the assumption of perfect markets in the model, the market pressure on each firm drives profits to zero, what leads into the zero profit condition $\pi_k = 0$. Replacing (5.41) in the zero profit condition, we have:

$$e_k^* = \frac{\phi_k}{\omega} \frac{\epsilon}{(1-\epsilon)} \tag{5.42}$$

This zero profit condition also allows to derive the prices. For this purpose the assumption of $\bar{i} = 2$ and $\bar{k} = 2$ holds, so that a theoretical solution can be determined. The specific step by step can be found in the appendix of Blanz (2019). Hence, we have:

$$^{p}b_k = \phi_k \left(1 + \frac{\epsilon}{1-\epsilon} \right) \left(\frac{\phi_k}{\omega} \frac{\epsilon}{1-\epsilon} \right)^{-\epsilon} \tag{5.43}$$

$$p_1^* = (\chi_1)^{-1} (\nu_{11}\nu_{22} - \nu_{12}\nu_{21})^{-1} (\nu_{22}{}^{p}b_1 - \nu_{21}{}^{p}b_2) \tag{5.44}$$

$$p_2^* = (\chi_2)^{-1} (\nu_{11}\nu_{22} - \nu_{12}\nu_{21})^{-1} (\nu_{11}{}^{p}b_2 - \nu_{12}{}^{p}b_1) \tag{5.45}$$

Household Optimization Problem

The households maximize their utility and choose their quantities Q, and y.

$$\max_{Q,y} U(Q, y) \; s.t. \; \omega = y + \sum_{i=1}^{\bar{i}} (\beta_i q_i) p_i \tag{5.46}$$

Solving this maximization problem, lead us to the quantities q_i^* demanded by consumers, and p_i^* willingness to pay for the fish. This function relates the amount of each species demanded (and consumed) to the prices of all available species.

$$q_i^* = \alpha^\eta p_i^{-\sigma} \beta_i^{\sigma-1} \left(\sum_{i'}^{\bar{i}} (p_i \beta_i)^{1-\sigma} \right)^{\frac{\sigma-\eta}{1-\sigma}} \tag{5.47}$$

$$p_i^* = \alpha \beta_i (\beta_i q_i)^{\frac{-1}{\sigma}} Q^{\frac{\eta-\sigma}{\eta\sigma}} \tag{5.48}$$

From this optimization procedure we derive an equation that describes the demanded quantity of one species in terms of the consumption given by the other. From the first order condition we have:

$$q_2 = \left(\left(\frac{p_1}{\alpha\beta_1} (\beta_1 q_1)^{\frac{1}{\sigma}} \right)^{\frac{\eta(\sigma-1)}{\eta-\sigma}} - (\beta_1 q_1)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} (\beta_2)^{-1} \tag{5.49}$$

The fishers maximization of profits and the utilities from the household, allows us to find the optimal number of firms practicing each mètier k (Eq. 5.50, 5.51). The assumption of $\bar{i} = 2$ and $\bar{k} = 2$, holds in order to find a mathematical expression that can be generalized. With these components the model is described.

$$n_1^*(q(\mathbf{p})) = \frac{\nu_{22}\chi_2 q_1(\mathbf{p}) - \nu_{12}\chi_1 q_2(\mathbf{p})}{e_1^{*\epsilon}\chi_1\chi_2(\nu_{11}\nu_{22} - \nu_{12}\nu_{21})} \tag{5.50}$$

$$n_2^*(q(\mathbf{p})) = \frac{\nu_{11}\chi_1 q_2(\mathbf{p}) - \nu_{12}\chi_2 q_1(\mathbf{p})}{e_2^{*\epsilon}\chi_1\chi_2(\nu_{11}\nu_{22} - \nu_{12}\nu_{21})} \tag{5.51}$$

5.B Model Calibration

We calibrate stocks, harvests, and prices for the whole North Sea, using the data provided by the International Council for the Exploration of the Sea (ICES) regarding landings (harvests) and stocks (SSB)(ICES, 2019a,b). Prices are calibrated using data from the EUMOFA (European Market Observatory for Fisheries and Aquaculture Products) database. The calibration involves the following steps:

1. *Ecosystem component*: The function describing the stock growth is calibrated using data of SSB for plaice and sole from the years 1957 to 2019 (ICES, 2019a,b). The data are transformed to a scale of the model through a scale parameter (κ) that represents the Maximum Sustainable Yield (MSY). The initial values of the parameters 'a' and 'b' of the Ricker-recruitment function are found by linearizing the function and fitting a linear model to the observed data (Equation.5.31), using the FSA (Simple Fisheries Stock Assessment Methods) library in R. Then, a non-linear least squares model based on those values of 'a' and 'b' is estimated. The fit between the model estimates and the real growth data is shown in figure 5.1.

2. *Household and Harvesting Components*: We calibrate household parameters using data prices for the years 2001-2020. We transform this prices to be relative to income to fit the scale of the model. We use the Gross Domestic Product (GDP) of the North Sea Countries as a proxy for the income used the model. Prices and GDP are adjusted for inflation to 2015 constant prices. To calibrate harvesting parameters, we use the same data as in the step one, combined with harvest data reported in landings for the whole North Sea by ICES (2021a,b)[6]. Using this data and the parameters already found in step one we construct an objective function to minimize the error between the predicted values of harvests and prices, and the real data (Equation 5.52). We use the existing implementation of the *nlminb* procedure in R to minimize these errors (ζ) (Nash et al., 2019)(Equation. 5.18, 5.48).

   To find the initial values of our final calibration procedure we use results of previous trials. During our calibration procedure we implement different trials to minimize the objective function. Using different weighted values, including more or less parameters or changing the time lapse for the calibration. The result of these trials gives many possible values for each parameter. Use choose the maximum and minimum values of each parameter and construct a matrix of 519 possible combinations that we use as initial values for our final calibration.

   Finally, we find the best fitting parameters for ϵ, χ_1, χ_2,ϕ, η, α, σ, β_1, and β_2 that ensure an interior steady-state and reflects the real relationships between quantities,

[6]The ICES (2021a,b) reports include landings, discards and catches. For our purposes we set landings equivalent to harvest because these are the quantities that are traded on the market.

harvest and prices. To identify the parameters that comply with an interior steady-state we set the quota as the last value of our data for the year 2020.

$$\min_{\hat{H}_i,\hat{p_i}} \zeta = \sum_{t=1957}^{2020} \sum_{i=1}^{2} m_i^h (\hat{H}_{it} - H_{it})^2 + \sum_{t=2001}^{2020} \sum_{i=1}^{2} m_i^p (\hat{p_{it}} - p_{it})^2 \tag{5.52}$$

subject to:

$$\epsilon,\ \chi_1,\ \chi_2, \phi,\ \eta, \alpha, \beta_1, \text{ and } \beta_2 > 0.000001$$
$$\sigma > 1.000001$$

where $\hat{H}_i$ is:

$$\hat{H}_{it} = \sum_{k=1}^{2} n_{kt} h_{ikt}(e_{kt}, x_{it}) = \sum_{k=1}^{2} n_{kt}(\nu_{ik} e_k^{\epsilon} x_{it}^{\chi_i})$$

$\hat{p_{it}}$ is:

$$\hat{p_{it}} = \alpha \beta_i (\beta_i q_{it})^{\frac{-1}{\sigma}} Q^{\frac{\eta-\sigma}{\eta\sigma}}$$

and m_i^h and m_i^p are weighted values for harvest and prices to normalize the calibration to the mean of the real values:

$$m_i^h = \frac{1}{\bar{H}_i} \text{ and } m_i^p = \frac{1}{\bar{p}_i}$$

5.C Adaptive Capacity Figures

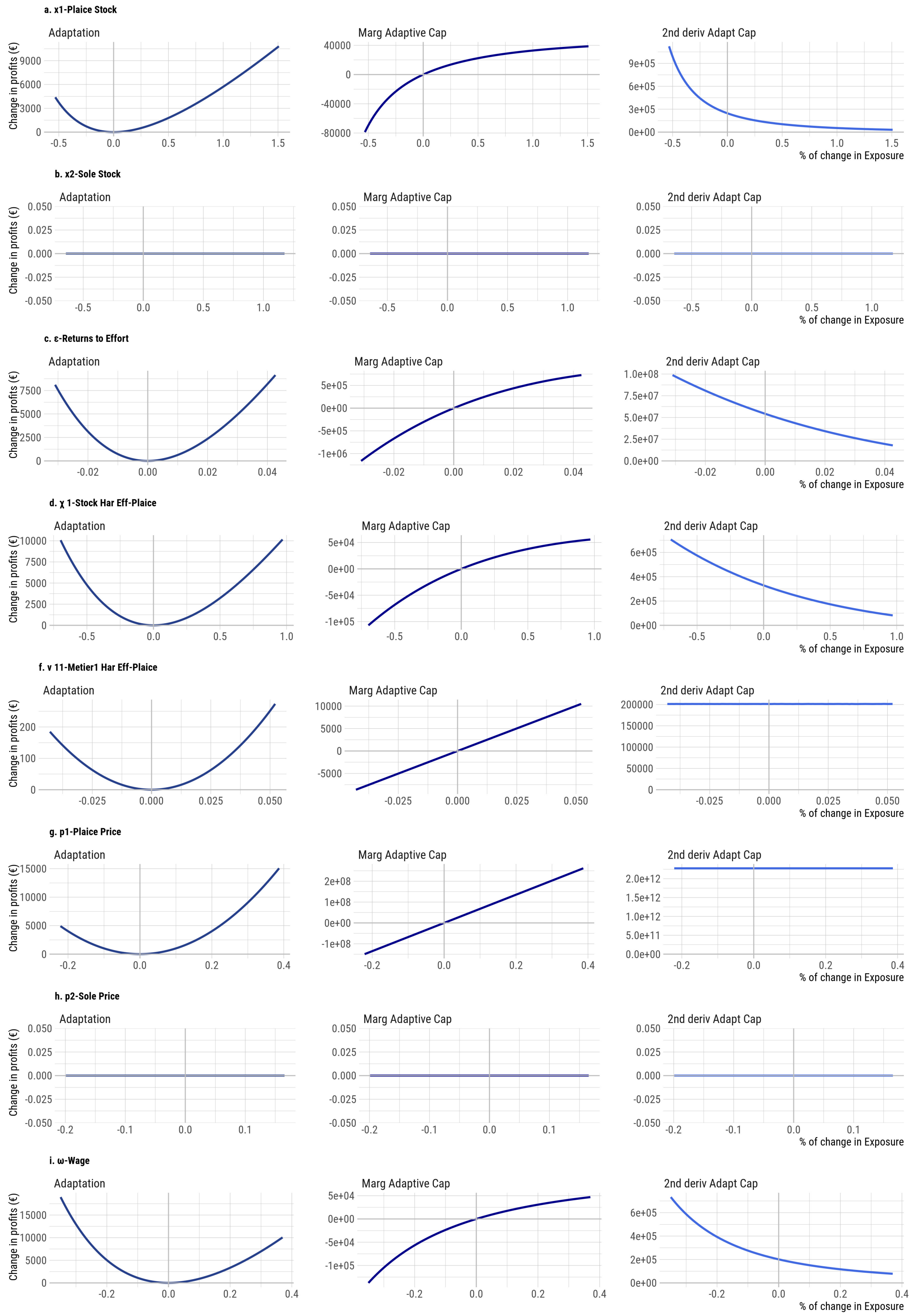

Figure 5.12: Adaptive capacities of métier 1 for ecosystem, harvesting and market drivers. The left column shows the Eq. (5.24), the center column shows the first derivative (Eq. 5.25), and the right shows the second derivative of adaptive capacity (Eq. 5.26)

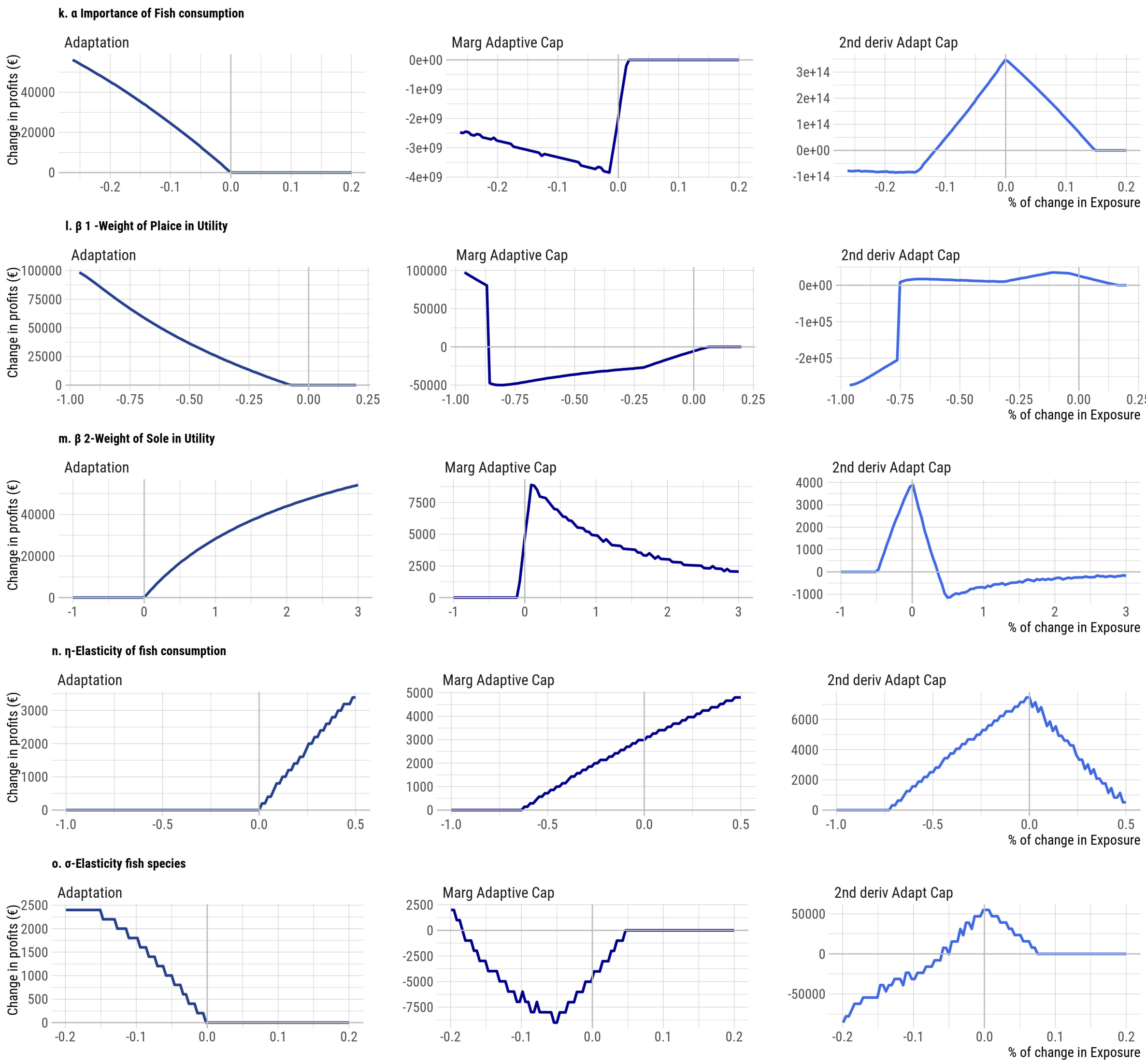

Figure 5.13: Adaptive capacities of métier 1 for household preference drivers. The left column shows the Eq. (5.24), the center column shows the first derivative (Eq. 5.25), and the right shows the second derivative of adaptive capacity (Eq. 5.26). The large step on the curves is due to issues in numerical precision. The functions at exposure zero result in a non-defined derivative since they are positive to one side and negative to the other.

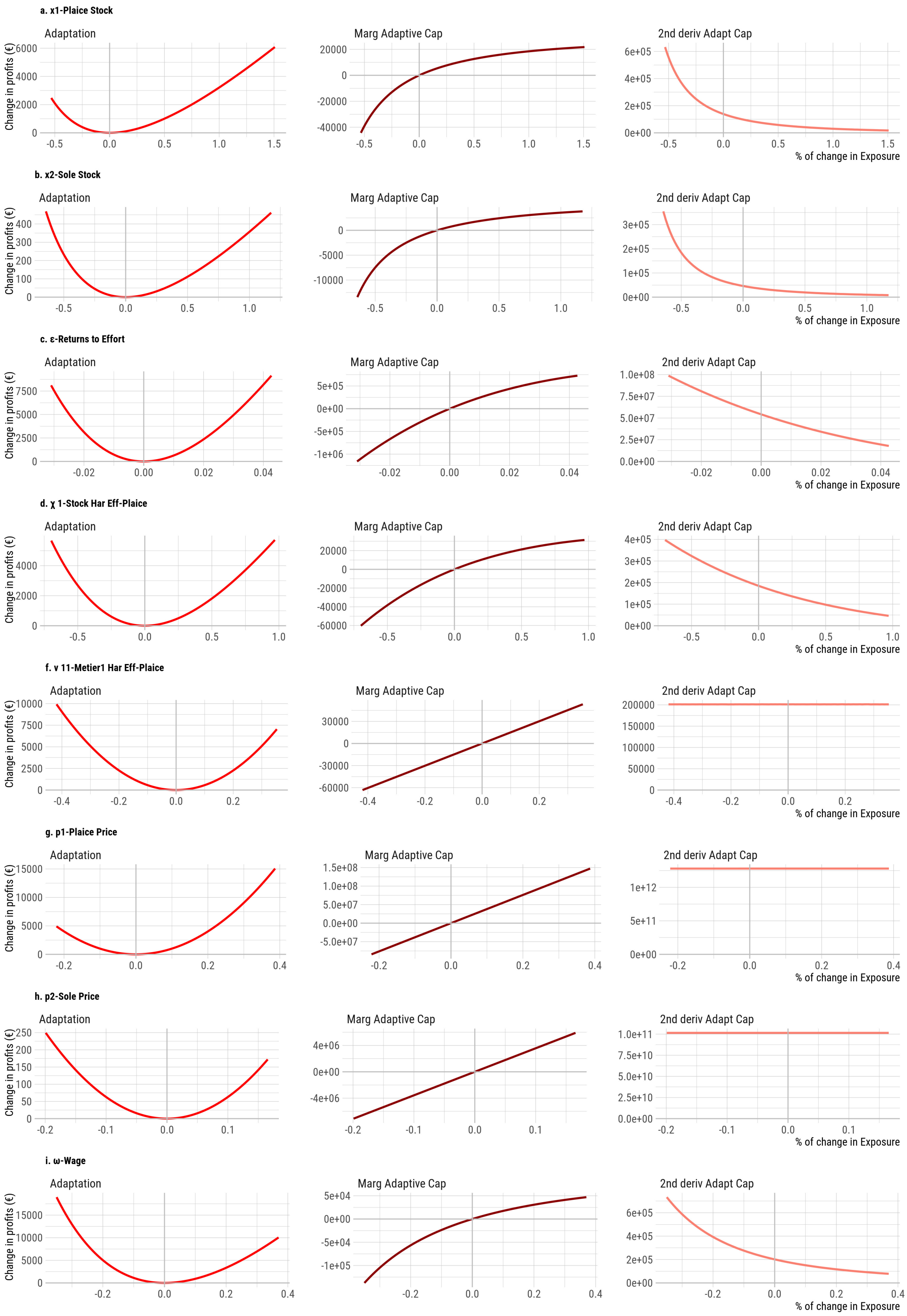

Figure 5.14: Adaptive capacities of métier 2 for ecosystem, harvesting and market drivers. The left column shows the Eq. (5.24), the center column shows the first derivative (Eq. 5.25), and the right shows the second derivative of adaptive capacity (Eq. 5.26). The large step on the curves is due to issues in numerical precision. The functions at exposure zero result in a non-defined derivative since they are positive to one side and negative to the other.

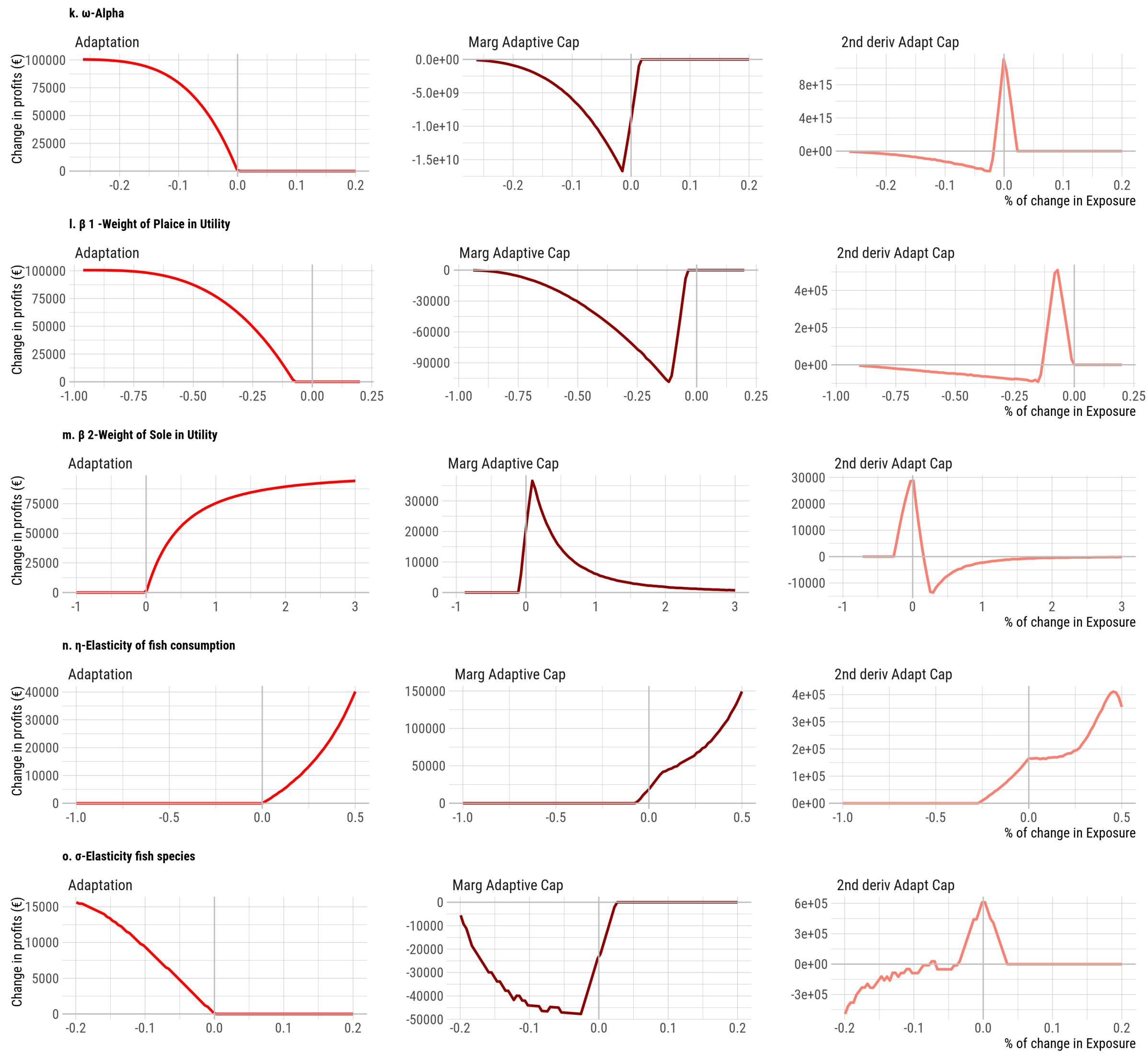

Figure 5.15: Adaptive capacities of métier 2 for household preference drivers. The left column shows the Eq. (5.24), the center column shows the first derivative (Eq. 5.25), and the right shows the second derivative of adaptive capacity (Eq. 5.26). The large step on the curves are due to numerical precision.

Chapter 6

Optimal Management of Fisheries with Interaction Effects

Abstract: Management of multi-species fisheries is made complicated by interaction between the different species involved. Interaction between species may take place within the ecosystem, through simultaneous inseparable harvesting or through consumer demand. While each of these types of interactions has been shown to be significant individually, analyses including all three are lacking. In this paper an analytical model of multi-species fisheries is used to determine optimal harvesting rates incorporating all three types of interactions. This is done in order to determine the consequences of omitting individual types of interaction and to investigate possible inter-dependencies. Furthermore, their importance in the design of total allowable catch and quantity tax based management is investigated. While ecosystem interactions between species are known to be important in setting optimal harvesting quotas, the significance of the other types of interaction is less obvious. Depending on the goals of the manager, their specific properties and the management method they may be omitted.
Keywords: Multi-Species Fisheries, Dynamic Modelling, Market Incentives, Compliance, Ecological-economic systems

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This chapter consists of the paper "Three Types of Interaction in Multi-Species Fisheries and When They Need to be Considered" presented at the 6th World Congress of Environmental and Resource Economists by Blanz (2018). Now in submission to Ecological Economics.

6.1 Introduction

Through fishery human actors have a direct impact on aquatic ecosystems. This impact may be compounded by interactions between multiple species within these ecosystems. Furthermore, fisheries are often indiscriminate, impacting multiple components of the ecosystem simultaneously, but even when selective harvests are possible human actors may prefer to consume harvests of the individual species simultaneously in certain proportions. Management of fisheries then is the attempt to control this human impact on fish stocks and the wider ecosystem of which they are a part and which sustains them. The goals motivating implementation of management measures may simply be to achieve maximal (sustainable) harvest rates, to sustain stock levels of a certain species, to ensure that biodiversity is maintained or to ensure that some other measure of ecosystem health is met. In short, the job of the fisheries manager is to ensure that fishery effort is based on society's preferences and not only those of fishers, by implementing appropriate laws and regulations.

Depending on the goal of the manager, the extent of knowledge required with respect to the managed ecosystem, but also of fisheries and societal preferences, is variable. To aid in structuring the known properties of the managed ecosystem and possibly its interaction with harvesters and consumers various models are used (Hollowed et al., 2000; Link, 2002b). These range from very simple representations of single species with exogenously set harvests (Pearl and Reed, 1977) to highly complex descriptions of fisheries and related ecosystems including as many details as possible (Pelletier et al., 2009). In any case, models are needed to organize and represent available data and systemic knowledge of the relevant systems. They are further needed in order to derive management measures from the available data.

Simple models have the benefit that they can be analytically solved in order to find general results that can be used across a wide variety of ecosystems, such as the maximum sustainable yield (MSY) of a given harvested species. However, excessive simplification may cause these general results to be of little use in management, when factors not included in the model may cause an ecosystem managed on such a simplistic model to fail. Harvest rates deemed sustainable may be fatal when cross impacts and ecosystem feedbacks are considered. Conversely, what is deemed the maximum sustainable harvest in a single species setting may not be the actual maximal sustainable harvest rate if positive or negative feedbacks in species growth where omitted (Ströbele and Wacker, 1991; Pikitch et al., 2004). Consequently, these types of models have long been considered too simplistic to be used as the foundation of management (Larkin, 1977).

Highly complex models, meanwhile, have significantly larger data and computational requirements in order to yield useful results (Link, 2002b). The necessary data to correctly calibrate and run such a model ranges from moderately difficult to practically impossible to obtain. Whereas prices of sold fish can be observed in the market with limited effort, estimating the state of the ecosystem or harvesting properties requires costly research vessels and operating expenses. Estimating consumer preferences and determining reactions in demand due to changing prices is an area of much research within economics, which has proven to be anything but simple. Furthermore, increasing complexity is the bane of tractability, implying that it is difficult to analytically derive general results using such models.

A basic rule when developing a model is to include as much complexity as is necessary, while keeping the model as simple as possible. The aim of modelling after all is to create parsimonious models that still have a high explanatory power. To aid in answering the question how much complexity is necessary, I attempt to give some indication as to what types of interactions between species need to be included in models of multi-species fisheries and which may be omitted in the name of simplicity. The three types of interaction between harvested species I consider are interactions between species within the ecosystem, technological interactions in harvesting between species and interactions between demanded quantities of different species by the final consumers of harvested fish. Each of these types of interaction has a large literature describing their individual importance for management. However, attempts to investigate possible inter-dependencies between them, causing positive or negative feedbacks between harvesting rates, appear to be quite rare. These types of interactions between interactions between species are of special interest, as they may cause unexpected behaviour in a system that was thought to be successfully managed. This is especially true for the human components, fishers and consumers, of the coupled ecological economic fisheries system (e.g. Fulton et al. (2011)).

Each of the avenues of interaction between the harvesting of different species, ecosystem interaction, technological interaction in harvesting and demand side interaction due to consumer behaviour change the way optimal management is conducted.

The first type of interaction, between species within the ecosystem, determines the capacity of the ecosystem to recuperate from harvesting. If harvests exceed this capacity they will not be sustainable. Crucially, if ecosystem interaction is present, the capacity of the ecosystem to recoup lost stocks depends on the composition of species remaining. Link (2002a) derives a lengthy set of questions, based on which a modeller may determine the importance of ecosystem interactions for the system to be modelled. Ecosystem interactions cause changes in one stock to have a feedback effect on another. A classical example of such feedbacks are predator-prey relationships between individual species. The impact of such relationships for management has been investigated by e.g. Yodzis (1994). But more complex relationships between more than two species may also need to be considered (May et al., 1979). In the same context Plagányi et al. (2014) describe that it would be unwise to manage multiple species in the same ecosystem as if they were independent. Various case studies have been performed illustrating the importance of considering ecosystem interactions for the fisheries modelled (e.g. Gulland and Garcia (1984)).

The second type of interaction, technological interactions in harvesting, also called bycatch, cause harvests of one species to be associated with simultaneous unavoidable harvests of another species. Impacts on parts of the ecosystem which are not harvested are also possible. The simultaneous unintended catch of a different species (Skonhoft et al., 2012; Nieminen et al., 2012) or age group (Davies et al., 2009) than that which intended is termed bycatch. Bycatch is caused by fishers not being able to perfectly select which species are harvested or by selectivity being costly (Abbott and Wilen, 2009; Singh and Weninger, 2009). However, fishers will not necessarily try to avoid bycatch. In multi-species fisheries the species caught as bycatch will often also have market value. In this case it will be landed and marketed and can be readily be included in management. Bycatch not brought to market however implies that fishers discard part of their catch at sea. This increased impact on ecosystems, over that caused by marketed quantities from discarding, is difficult to estimate due to reliance on self reported data by fishers. Davies et al. (2009) estimate that at least 40 % of total fishing mortality is not due to marketed harvests but discarding. The incentives of fishers to discard are determined by the relative contribution of caught species to individual profits. These critically depend on market prices and quantities demanded by consumers or set by regulation.

The third type of interaction, demand side interactions between different species are caused by the preferences of final consumers for fish products of individual species and their relative amounts. These preferences are reflected in the household demand functions which constitute the demand side of the market for fish products. It has been shown that consumer preferences may have a significant impact on the state of the ecosystem by driving harvests through their impact on prices (Baumgärtner et al., 2011). In light of empirical evidence (Barten and Bettendorf, 1989; Bose and McIlgorm, 1996; Asche et al., 1997; Chiang et al., 2001) that different species of fish are viewed as imperfect substitutes by households Quaas and Requate (2013) show that even when species are independent in their ecological and harvesting properties, substitution between species by consumers may lead to sequential overfishing of all available species.

Determining appropriate management measures is further complicated by the fact that these different avenues of interaction between species are not independent of each other. Changing ecosystem stocks impact harvesting rates which impact prices, prices in turn incentivise fishers to adjust harvesting rates which in turn impact ecosystem stocks, either amplifying or dampening this cycle. Each of these avenues of interaction causes feedbacks between the stocks of individual species. These feedbacks may strengthen the effect of interaction between species or compensate each other, thereby weakening the interaction. It is even possible that different avenues of interaction cancel each other out with regards to the actual impact on the ecosystem. Such a case is investigated by Blanz (2019). Therein a condition is derived under which changing amounts of bycatch/technological interaction have no effect on harvest rates. This is possible as harvest rates depend not the only on the harvesting efficiencies of the different gear types but also on the size of the respective fleets using the respective gear types. Thereby, it is possible that scenarios with different gear effectivities obtain identical results with regard to harvest rates. The different harvesting efficiencies are perfectly offset by changes in fleet composition. To explain these changes in fleet composition, market demand needs to be included in the model. Market demand adapts in response to the changes in supply, caused by changed catch composition. However, the conditions necessary for this effect to perfectly cancel out impacts from technological interaction between ecosystem stocks are very narrow, implying that in the general case technological interaction between species in conjunction with market forces appears to be especially relevant to determining the effectiveness of management measures. Squires et al. (1998) investigate compliance with individual transferable quota (ITQ) based management schemes and find that fishers have an increased incentive to discard part of their catch, when the relative proportions of harvested species do not match those prescribed by the ITQ. A similar issue is described by Beddington et al. (2007). Regarding incentives of individual fishers to discard part of their catch when regulated by quotas, Abbott and Wilen (2009) model the choice problem of fishers in a game theoretic context. They find that the decision maker is severely restricted in choosing harvesting quotas, if large amounts of discards are to be avoided. As an alternative to management using quotas I describe the implementation of management through taxes on quantities, which can either be applied to prices paid by consumers or as a landing fee for harvesters.

In the context of all these interactions and their inter-dependencies that potentially need to be considered when designing effective management measures, the focus of this paper are the consequences of the inter-dependency of technological and demand side interaction for the design of management measures. To this end the socially optimal harvest rates are analytically determined, while taking into account ecosystem, technological and demand side interactions between species. The implementation of these harvesting rates through different management measures is then analysed to determine their effectiveness, given the three types of interactions and their inter-dependencies.

The remainder of the paper is structured as follows: In the following section (Section 6.2) the model equations characterising the ecosystem, harvesters and household preferences, each including the possibility for interaction between species, are presented. Furthermore the market equilibria, resulting from the interaction of harvesters profit maximizing behaviour and consumer demand or socially optimal demand, are derived. The implementation of different management measures to achieve the derived socially optimal harvesting rates and investigation of their expected effectiveness given the behaviour of the human actors are performed in Section 6.3. The results of these efforts, with respect to the three types of interactions between species described in this paper, as well as limitations of the analysis are discussed in Section 6.4. Concluding remarks are given in Section 6.5.

6.2 The Model

In order to demonstrate the combined effect of the three types of interaction between different species the model needs to incorporate each type and allow interaction between the components containing the respective types of interaction. Tractability of the model requires limiting the analysis to two species and harvesting gear types. While this prohibits analysing cases where entire foodwebs are relevant to setting optimal harvest rates, other types of ecosystem interaction can be considered, regardless. It is expected that results obtained in this reduced model will apply analogously to cases with more species and harvesting tools.

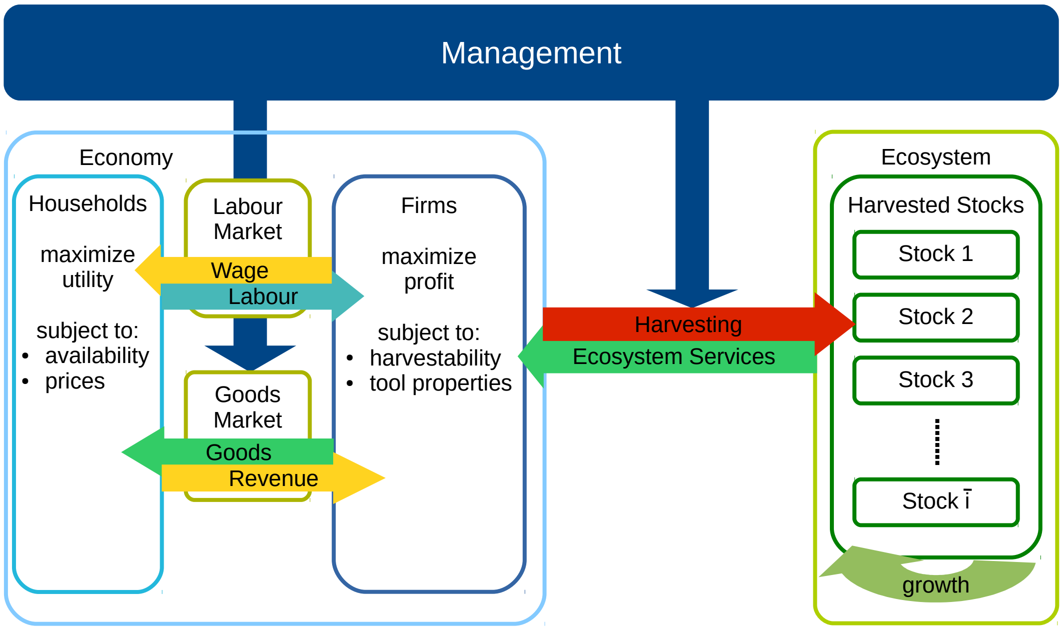

Figure 6.1: Components of the model and their interactions. Within each component species stock levels or their corresponding harvest rates may interact. Harvesting is performed using multiple different gear types, each with different harvesting efficiencies for each of the species included in the model.

The components of the model are shown in Figure 6.1 and are presented in greater detail in the subsections below. The model consists of an ecosystem component, describing its current state and dynamics, harvesting firms, maximizing profits, and consumers, maximizing contemporaneous utility. Between harvesting firms a market for goods allows for the sale of harvested ecosystem stocks to consumers. The prices on this market and corresponding harvested quantities are determined endogenously. A second market for labour allows firms to employ labour provided by households in harvesting or manufacturing of a numeraire commodity, thereby providing income to households, needed in order to pay for the fish and other products consumed. Management may either influence harvested quantities directly or through taxes on the goods market. As it is an analytical model the components are kept as simple as possible, in order to have tractable solutions, while still reproducing all of the avenues of interactions between species discussed in the introduction.

In order to include ecosystem interaction, the stock growth equations include inter-species competition. While this does not represent more involved predator prey interactions, it is sufficient to ensure that the partial derivatives of stock growth of one species to the others is not zero. This is required in order for the optimal harvesting rate to also depend on the growth of all stocks. With this present, the exact form that the ecosystem equations take is not relevant for the general results as to the importance of ecosystem interaction in management.

Technological interaction in harvesting is implemented through catch efficiency vectors for each of the available harvesting gear types. Thereby each gear has a parametrised catch efficiency for all available species. This allows investigation of cases with or without bycatch in a general manner. This also allows determining conditions on when technological interactions can be ignored as they are perfectly compensated for by other effects. Fisher behaviour is modelled as that of profit maximizing firm endogenously determining optimal harvesting rates given demand and market pressures.

Interaction between species through the demand side of the fish market is created by household preferences that allow for a parametrised limited degree of substitution between different species in consumption. From these the household demand function is derived, which relates demanded quantities of a specific species to the prices of all available species. If the price of another species falls, the household may substitute consumption of the cheaper species for that of the more expensive one.

The model was extended from Quaas and Requate (2013) to include technological interaction in harvesting and incorporate ecosystem interaction as in Baumgärtner et al. (2011) by Blanz (2019) and solved for an open-access setting without any management. In this paper that analysis is further extended by the inclusion of a social welfare function aggregating household utility over time and derivation of socially optimal harvesting rates. The equations and derivations in this section are reproduced from Blanz (2019) in order to provide a foundation for the following sections.

In the remainder of this paper the sets of species and the set of harvesting gear types included in the model are given by I and K respectively. Species are indexed by i and harvesting gear by k. As an example, the stock of species i is given by x_i and harvesting efficiency for species i using gear type k is given by ν_{ik}.

$$I = \{1, 2\} \quad K = \{1, 2\} \tag{6.1}$$

6.2.1 Ecosystem Dynamics

Each of the species in the system is represented by a stock variable tracking the current biomass relative to the carrying capacity of the ecosystem for that species. The state of the ecosystem at time t is given by the vector $\vec{x}_t$ of length $\bar{i}$ with entries x_i for each species. Stock change (6.2) is determined by the difference of intrinsic growth of the species, depending on the state of all species, and total harvests.

$$\dot{x}_{it} = g_{it}(\vec{x}_t) - H_{it}(\vec{x}_t) \tag{6.2}$$

The mode includes a logistical growth function for the intrinsic stock change component g_{it}. However, the analytic results derived below do not depend on that exact shape of the intrinsic growth function, only whether the cross derivatives between species are zero. For the equation below this is the case whenever the matrix $\boldsymbol{\gamma}$ containing the interspecies competition vectors $\vec{\gamma}$ is not equal to the identity matrix and contains non-zero elements off the diagonal.

$$g_{it}(\vec{x}) = r_i(x_i - \underline{x}_i)\left(1 - \frac{\vec{\gamma}_i \vec{x}_t}{\kappa_i}\right) \tag{6.3}$$

$$\frac{\partial g_i(\vec{x})}{\partial x_{i'}} \neq 0 \quad i \neq i' \quad i, i' \in I \tag{6.4}$$

According to the logistic growth function (6.3) a stock will grow as long as it is above the species specific minimum viable biomass threshold $\underline{x}_i$ until it reaches the carrying capacity of the ecosystem for this species κ_i which may be shared with other species depending on the per species competition described by γ_{ij}, the elements of the species specific interspecies competition vector $\vec{\gamma}_i$. In the case with no interspecies competition $\gamma_{ij} = 0 \; \forall \; i \neq j \; \in I$.

The stock change and optimal management equations are the only time dependent components of the model. All other equations of the model depend only on the current state of the ecosystem. In the remainder of the paper any state variable without a time index t is defined to be contemporary.

6.2.2 Harvesting

Total harvests per species H_i are determined by the size of the fleets n_k operating harvesting gear k in the set of harvesting gear types available K and the harvest of that species per vessel using each gear type $h_{ik}(e_k, x_i)$. It is assumed that for each species in the model there is one gear type targeting it, with the possibly of simultaneously catching other species as bycatch. Consequently, there are $\bar{k} = \bar{i} = 2$ gear types in the model. This assumption is based on the logic that if there were more gear types than species available, only the most efficient would be used, depending on which species is targeted. Fishers using the more efficient gear could undercut prices of those using less efficient gear. Other fishers would either leave the market or change their gear type. In the model such changes in gear type are reflected as changes in the fleet composition.

$$H_i = \sum_{k=1}^{\bar{k}} n_k h_{ik}(e_k, x_i) \tag{6.5}$$

Harvests of species i per vessel using gear k depend on the stock dependent availability $\chi_i(x_i)$ of species i in combination with the gear specific harvesting efficiency ν_{ik} and the harvesting effort e_k. The additional catch for each additional unit of effort depends on the returns to effort ϵ. Stock dependence of harvesting is described by $\chi_i(x_i) = x_i^{\chi_i}$ where a specific form is needed. In the remaining sections $\chi_i(x_i)$ is abbreviated as χ_i, while $\boldsymbol{\chi}$ indicates a square matrix with the χ_i along its diagonal.

$$h_{ik}(e_k, x_i) = \chi_i(x_i)\nu_{ik}e_k^{\epsilon} \tag{6.6}$$

The harvesting effort e_k is determined endogenously for each gear type. Fishers are modelled as profit maximizing firms each operating a single fishing gear k with an endogenously determined amount of effort e_k. Each fishing gear is intended to catch one of the modelled species as its target but may also catch any other species, depending on the gear specific harvesting efficiencies ν_{ik} for each of the species i. All fishers operating a specific gear k are assumed to be identical. The fishers' profit function is given by the difference between revenues from selling all fish caught using a selected gear and total costs. Costs consist of fixed gear specific costs χ_k and variable costs depending on harvesting effort ω.

$$\max_{e_k} \sum_{i=1}^{\bar{i}} h_{ik}(e_k, x_i)p_i - \omega e_k - \phi_k \tag{6.7}$$

Maximizing the gear specific profit function yields the profit maximal effort dependent on the vector of current prices $\vec{P}$ and harvesting properties. In the case without bycatch, optimal harvesting effort per tool would only depend on the species it is intended to catch, as the elements of $\vec{\nu}_{k\neq i}$ would be equal to zero.

$$e_k^{**}(\vec{P}) = \left(\frac{\epsilon \vec{P}^{\intercal} \boldsymbol{\chi} \vec{\nu}_k}{\omega} \right)^{\frac{1}{1-\epsilon}} \tag{6.8}$$

In the case that perfect competition exists on the fisheries market, profits would be driven to zero. Any fisher achieving positive profits could decrease prices in order to take a larger portion of the market. Zero profits in combination with profit maximal effort yield the zero-profit optimal effort level e_k^* depending only on cost parameters and returns to effort.

$$e_k^* = \frac{\phi_k}{\omega} \frac{\epsilon}{1-\epsilon} \tag{6.9}$$

Given the behaviour of each of the individual vessels using a certain harvesting gear, total harvests are determined by the size of the respective fleets using each gear type, as stated in the beginning of this section. Fleet sizes are determined by the balance of supply and demand on the market for fish. This is formalised in the goods market clearing condition.

$$q_i(\vec{p}) = H_i = \sum_{k=1}^{\bar{k}} n_k h_{ik}(e_k, x_i) \tag{6.10}$$

Total supply of fish of each species must equal demand for that species $q_i(\vec{p})$. If harvests are not completely independent, i.e. bycatch is present in harvesting, the possible consumption levels q_i are limited by harvesting gear selectivity and non-negativity of fleet sizes.

$$n_k \geq 0 \;\forall k \in K \tag{6.11}$$

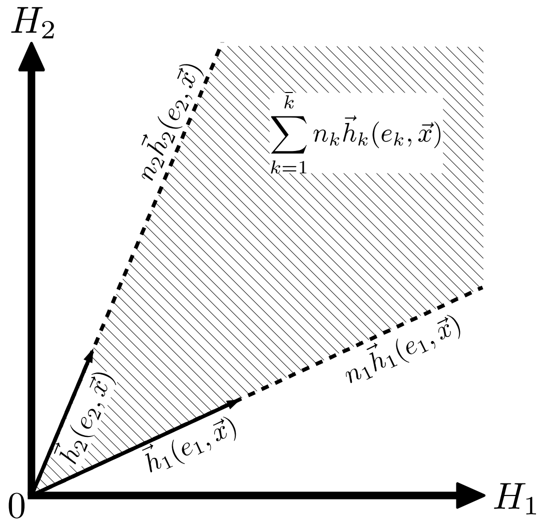

Figure 6.2: Feasible catch compositions of harvested species for the case with two harvesting gear types and two species. Gear types 1 and 2 have species 1 and 2 as their targets, catching the respective other species as bycatch. Given positive stocks of both species, harvest of only one species is impossible. The degree of bycatch determines the angle of the harvesting vectors. The size of the fleets n_1 and n_2 using each of the tools determine total harvests within the shaded area. Combinations of harvests outside the shaded area are only possible by discarding part of the catch.

Hence, the supply side of the market for fish is limited to positive linear combinations of the gear specific harvesting vectors $\vec{h}_k(e_k, \vec{x})$ containing the $h_{ik}(e_k, x_i)$ as elements. For strictly positive combinations ($n_k > 0 \;\forall k \in K$) the supply side can provide any composition of species. For other cases, where not all gear types are in use, the species composition of supply is fixed to that of the catch using the remaining gear $\vec{h}_k(e_k, \vec{x})$. In these edge cases, consumer choice is limited to the number of bundles containing the fixed ratio of harvested species. This restriction in harvestable catch composition is illustrated in Figure 6.2 for the case with two gear types $K = 1, 2$ targeting two species. Total harvest rates for each species H_1 and H_2 are depicted along the axes. The degree of bycatch in harvesting defines the angle of each of the gear harvesting vectors. In the case without bycatch they would lie along the axes, in combination spanning the entire harvest space. With bycatch however, given that negative fleet sizes are not possible, combinations of the harvesting vectors only span a subspace of species compositions in harvest. This will become relevant in the household consumption and optimal harvesting decisions below. Areas outside of the spanned space can only be reached if parts of the catch are discarded.

If these harvest combinations are sufficiently more profitable than selling the harvestable catch compositions, discarding becomes economically attractive.

6.2.3 Households

The demand function for fish and optimal harvesting rates are derived from the household preferences represented in the household utility function of a single representative household. Utility is gained from the sub utility for consumption of fish Q and consumption of a composite manufactured good y representing all other consumption. The relative importance of fish consumption compared to other consumption is measured by $\alpha \geq 0$, the elasticity of fish consumption is by $\eta > 0$.

$$U(Q, y) = \begin{cases} y + \alpha \frac{\eta}{\eta - 1} Q^{\frac{\eta-1}{\eta}} & \text{for } \eta \neq 1 \\ y + \alpha \ln Q & \text{for } \eta = 1 \end{cases} \tag{6.12}$$

Preferences for the consumption of individual fish species are modelled as a Dixit-Stiglitz utility function (Dixit and Stiglitz, 1977). This is characterised by a constant elasticity of substitution between different species $\sigma > 0$. Higher values of σ indicate that individual species are better substitutes for each other, the households care less about the composition of consumed fish products and more about the quantity.

$$Q = Q(\vec{q}) = \left(\sum_{i=1}^{\bar{i}} q_i^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \tag{6.13}$$

Household consumption decisions are limited by the budget restriction. The representative household receives income ω from providing labour to either the fishery sector or the manufacturing sector. The amount of labour provided by the household is normalised to unity. The wage rate ω is assumed to be equal across both sectors. Income is spent in order to purchase fish products q_i at market prices p_i or manufactured goods which take the role of numeraire commodity, with unity prices.

$$\omega = y + \sum_{i=1}^{\bar{i}} p_i q_i \tag{6.14}$$

From these equations the demand function for each fish species depending on prices of all species in the market can be derived. In so doing the inverse demand function can also be derived, relating the willingness to pay for a quantity of a specific species, given the quantities consumed of the other species. These derivations are reproduced in Appendix 6.B.1 and 6.B.2 respectively.

$$q_i = \alpha^\eta p_i^{-\sigma} \left(\sum_{i'=1}^{\bar{i}} p_{i'}^{1-\sigma} \right)^{\frac{\sigma-\eta}{1-\sigma}} \tag{6.15}$$

$$p_i = \alpha q_i^{-\frac{1}{\sigma}} Q^{\frac{\eta-1}{\eta} - \frac{\sigma-1}{\sigma}} \tag{6.16}$$

However, whenever harvests of the individual species are not independent due to bycatch, this may further restrict consumer consumption choices. As is described in the previous section, in this case fisheries are not able to supply all possible combinations of fish quantities. In the edge case where consumers prefer the combination of species harvested using one of the gear types to all other quantity combinations, consumers do not choose individual amounts but instead choose the number of bundles with that combination of species to consume. The reformulation of the utility function to consider bundles of fish quantities and the derivation of the corresponding demand function is shown in Appendix 6.B.4. Demand is then no longer expressed as a set of functions relating individual consumed quantities of species to market prices, but a single function relating the number of bundles consumed to costs required a single bundle and the species composition of that bundle. Given the assumed goods market clearing, the number of bundles demanded (6.17) will be equal to the fleet size using the relevant gear and the species composition of the bundle is given by the catch composition of the same gear.

$$n_k = c_k^{-\eta} \alpha^\eta \left(\sum_{i=1}^{\bar{i}} h_{ik}(x_i)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{(\eta-1)\sigma}{\sigma-1}} \tag{6.17}$$

The condition to switch from the free to the restricted demand function depends on the degree of substitution between species as well as the stock specific and gear specific harvesting efficiencies. Its derivation from the household optimisation problem is shown in Appendix 6.B.5.

$$0 > \sum_{i=1}^{\bar{i}} (\chi_i \nu_{i2})^{\frac{\sigma-1}{\sigma}} \left(\frac{\nu_{i1}}{\nu_{i2}} - 1 \right) \tag{6.18}$$

6.2.4 Manufacturing Sector

Finally, the model is closed by determining the amount of the numeraire commodity available to consumers. To simplify the analysis it is assumed that the numeraire commodity, the manufactured good y is produced with labour as the sole input at a constant productivity equal to the wage rate. A perfect labour market is assumed ensuring that the wage rate ω is equal across all sectors and equal to marginal productivity of labour in the manufacturing sector. This simplification is deemed reasonable as the focus of the analysis done with the model is the fisheries market and changes in harvesting technology. Production of the numeraire commodity available to consumers is then determined as total production given the labour available left over after subtracting that used for economy wide fixed costs. Labour available to production is given by the difference between labour employed in the harvesting industry and total labour provided by households, normalized to unity.

$$y = \omega \left(1 - \sum_{k=1}^{\bar{k}} n_k e_k \right) - \sum_{k=1}^{\bar{k}} n_k \phi_k \tag{6.19}$$

With this the model is fully defined. The solutions to the market equilibrium for fish are presented below for an open-access and optimal demand setting. The open-access solution to the market equilibrium stemming from market interaction between harvesters and households was derived by Blanz (2019) and is reproduced below in order to be compared to the socially optimal solution derived in this paper.

6.2.5 Open-Access

Under open-access harvest rates are determined through the market equilibrium between utility maximizing households and profit maximizing firms. The market is assumed to have perfect competition driving profits of individual harvesters to zero. Harvest rates in the free market equilibrium only depend on the current state of the ecosystem. Ecosystem dynamics and interactions between species are irrelevant. Interactions in harvesting and demand side interactions, however, do have an impact on the market equilibrium. Technological interactions determine the feasible set of harvesting rates described in Section 6.2.2. The solution to the open access market equilibrium then depends on the case of the demand function, appropriate to the edges of the harvesting set or within it. In the first case the market equilibrium lies within the space spanned by the harvesting vectors, the shaded area in Figure 6.2, in the second it lies on the borders. The first case is characterised by both gear types being in use. The overall composition of harvests can be changed freely. Within this case, technological interactions may be irrelevant under certain conditions. The second case implies that only one gear type is in use, dictating the proportion of the species available to the market. .

The market equlibria for both cases under open-acces presented below are derived in Blanz (2019) and reproduced here to enable comparison with the solutions under socially optimal demand. The steps of the derivation are reproduced in Appendix 6.B. A result from that paper used when analysing the importance of the different types of interaction in the following is the condition for no effect of bycatch (6.23). When these conditions are met, the properties of technological interactions have not effect on prices, harvest rates or stocks. These conditions are used in the sections discussing optimal management. The open-access market solutions are used to evaluate the different management measures by analysing their impact on the open-access market equilibria. They are further used to determine incentives for deviation from prescribed harvesting rates by the economic actors.

The two cases of the market equilibrium depending on harvesting rates being limited by the feasible set or not are presented below. In the first case harvesting composition is not limited by technological interaction. In the second case proportions of species in harvests are limited to that in the catch of a specific gear type.

Case 1: All Gear Types in Use

As there are assumed to be no distortions on the market for harvested fish, fishers may freely enter or leave the market. This causes profits of fishers to be driven towards zero. Prices are then equal to the minimum average harvesting costs per species. Harvesting by individual firms is performed at the zero profit, profit maximal effort levels. Average harvesting costs are determined over all gear types available that harvest a specific species.

$$\begin{pmatrix} p_1 \\ p_2 \end{pmatrix} = \boldsymbol{\chi}^{-1} \left(\boldsymbol{\nu}^\intercal\right)^{-1} \begin{pmatrix} \phi_1 \left(1 + \frac{\epsilon}{1-\epsilon}\right) \left(\frac{\phi_1}{\omega} \frac{\epsilon}{1-\epsilon}\right)^{-\epsilon} \\ \phi_2 \left(1 + \frac{\epsilon}{1-\epsilon}\right) \left(\frac{\phi_2}{\omega} \frac{\epsilon}{1-\epsilon}\right)^{-\epsilon} \end{pmatrix} \tag{6.20}$$

Market prices depend on the properties of all gear types available to the harvesters. The derivation of the minimum harvest cost equation with free harvesting combinations between species (6.20) is reproduced in Appendix 6.B.2.

The Fleet composition using each of the tools is determined by balancing supply and demand, satisfying the goods market clearing condition (6.10).

$$\begin{pmatrix} n_1 \\ \\ n_2 \end{pmatrix} = \left(\boldsymbol{\nu} \ \operatorname{diag}(e^{\vec{*}\epsilon})\right)^{-1} \boldsymbol{\chi}^{-1} \ \vec{q}(\vec{p}) \tag{6.21}$$

Quantities demanded of each of the species depending on prices $\vec{q}(\vec{p})$ are defined by the household demand function for the case with free combinations of individual species (6.15). Hence, harvested amounts do not only depend on harvesting properties and technological interactions contained therein but also on preferences of households and demand side interactions between species. In this case, where households may freely choose the relative amounts of species consumed, changes in prices will consequently lead to shifts in the demanded quantities of each of the species. The mechanism behind this adjusting behaviour of demand can be seen in Figure 6.3. In that figure a simultaneous market equilibrium on the markets for both species is shown. The supply and demand functions for the first and second species, depending on prices of both species, are shown in the front and read section of the figure respectively. The current market equilibria for each of the species depending on only their respective prices are shown in sub panels (a) and (b). These are obtained by slicing the multidimensional markets at the levels of the prices for the respective other species, indicated by the dashed lines.

An increase in the price for species 1, due to changed ecosystem stocks, changes in harvesting parameters or management measures, shifts up the corresponding price plane. This upward shift is reflected by an upward shift in the supply curve in sub panel (a). However, simultaneously, the increase in the price of species moves the market equilibrium for species 2 along the intersection of the supply and demand planes on that market. This movement along the functions would be mirrored by an upward shift of the demand function in sub panel (b). This simple example explains why managing different species as if the demanded quantities where independent, may lead to unexpected results, even in cases where harvesting costs are independent of each other.

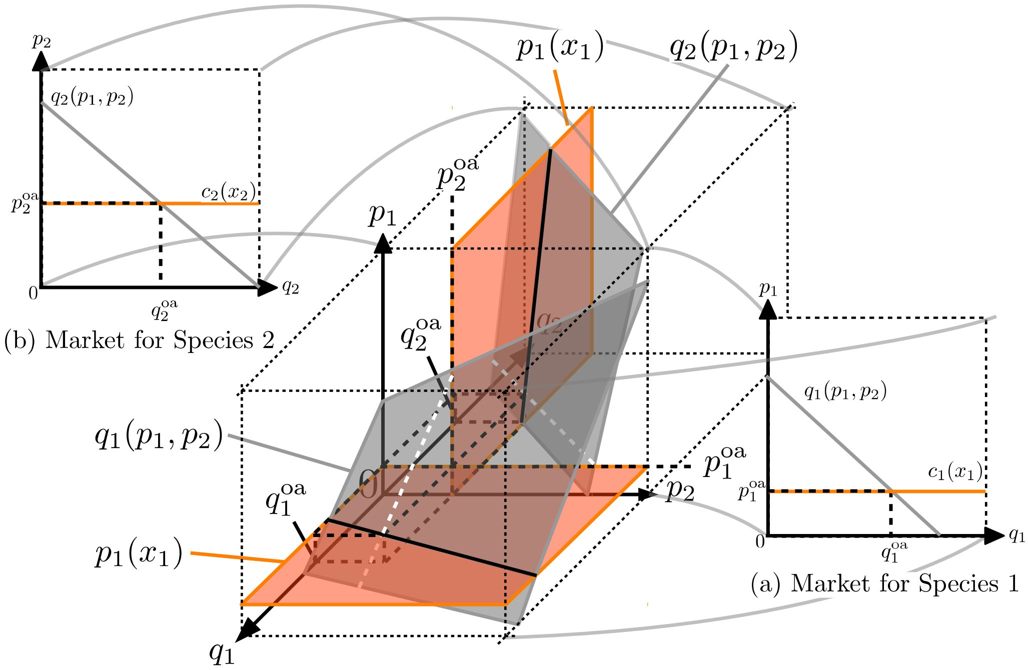

Figure 6.3: Sketch of simultaneous market equilibria for both fish species when both gear types are in use. The market equilibria for the individual species are shown in sub-panels (a) and (b) for Species 1 and 2 respectively. Market demand functions depend on the price of both species. The market supply planes only depend on the stock of their respective species. The bold lines along the intersections of the supply and demand planes indicate possible market equilibria for each of the two markets. The global equilibrium is found where the these curves, projected into either the price space (p_1, p_2) or the quantity space (q_1, q_2), intersect. The feasible set of combinations for q_1 and q_2 derived in 6.2.2 cannot be shown in this representation.

Regarding technological interactions in harvesting, it would appear that any difference in parametrisation of catch efficiencies would also influence harvesting costs, prices, quantities demanded and finally stocks. But this is not necessarily the case. As is shown below, under certain conditions different parametrisations of catch efficiencies may yield identical results.

Conditions for no Effect of Technological Interaction

Only when both gear types are in use is it possible that changes in fleet composition perfectly offset differences in harvesting efficiency parametrisations.

$$n_k > 0 \, \forall k \in K \tag{6.22}$$

Furthermore costs of the gear types under consideration need to satisfy equation (6.23) with regards to their relative expensiveness and relative total harvesting efficiencies of both tools, conditioned on the returns to effort in harvesting.

$$\frac{\phi_1}{\phi_2} = \left(\frac{\nu_{11} + \nu_{21}}{\nu_{12} + \nu_{22}}\right)^{\frac{1}{1-\epsilon}} \tag{6.23}$$

If bycatch intensity is interpreted as a change in species composition of harvests with a given harvesting gear, but not a change in total harvests using that gear, the sum of the individual harvesting efficiencies of each of the gears will remain constant $\nu_{1k}+\nu_{2k} = \text{const.}$ The derivation of these conditions first shown by Blanz (2019), is reproduced in Appendix 6.B.6 for the reader's convenience.

If these conditions are met, technological interactions in harvesting can be ignored in modelling. This condition together with the further restriction that ecosystem interactions may not be present also applies to the optimal management solution derived in Section 6.2.6.

Case 2: One Gear Type in Use

When the quantities of market equilibrium are limited to multiples of one of the harvesting vectors, the quantities demanded by consumers determining the market equilibrium are derived as follows: The size of the fishing fleet, using the single gear, is determined by the single tool demand function (6.17) depending on harvesting costs and catch efficiency. The corresponding quantities are determined by the total harvesting equation (6.5) combining fleet size and per vessel harvests. Prices are determined according to the inverse demand function (6.16) depending on the quantities. The three relevant equations are repeated below for the benefit of the reader.

$$n_k = c_k^{-\eta} \alpha^{\eta} \left(\sum_{i=1}^{\bar{i}} h_{ik}(x_i)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{(\eta-1)\sigma}{\sigma-1}} \tag{6.17}$$

$$q_i = H_i = \sum_{k=1}^{\bar{k}} n_k h_{ik}(e_k, x_i) \tag{6.5}$$

$$p_i = \alpha q_i^{-\frac{1}{\sigma}} Q^{\frac{\eta-1}{\eta} - \frac{\sigma-1}{\sigma}} \tag{6.16}$$

6.2.6 Optimal Harvest

To determine the socially optimal harvesting rates for all species, taking into account all three types of potential interaction between species, an all knowing benevolent social planner or manager is assumed. The aim of this manager is to maximize household utility not only for the current period but also for all future periods. The relative importance between utility today and in the future is given by the social discount rate ${}^{t}\rho$. In order to maximize inter-temporal household utility, harvest rates are set such that ecosystem stocks grow to the optimal amount with regards to possible sustainable harvests. Once these stock levels are reached the system will be kept in a steady state, where harvests equal stock growth in each period. This long term optimal steady state is determined below. While the optimal dynamics leading into the steady state appear to intractable, derivatives of the steady state with respect to model parameters or state variables can readily be analysed.

Comparing the harvest rates determined for the steady state under optimal access it is immediately obvious that they will be lower than those under open-access given identical stock levels. However, the higher open-access harvesting rates would deplete stocks. The open-access steady state will then have lower harvesting rates than those under optimal management. The differences between the market results under open-access and optimal harvesting for species are shown qualitatively in Figure 6.4. The optimal demand function, incorporating the shadow prices of stock depletion μ_1 is shifted downward from that under open-access. Alternatively, shadow prices can be thought of as a mark-up on market prices p_1^{oa}, evaluated by the short term demand function. Lower demand combined with unchanged harvesting costs result in the lower optimal harvesting rate q_1^*. However, due to only incorporating the market for one of the species, this figure belies the additional complexity in the analysis stemming from interactions between species. It is included here to aid the intuition of the reader. It should be understood in context with Figure 6.3. Hence, a shift in the demand curve is actually a shift of the demand plane, depending on both prices, occurring simultaneously in both markets.

The goal of the all knowing benevolent manager is measured by welfare W. This includes harvests in all periods of the model. Hence, the derived socially optimal harvest rates do not only depend on the current state of the ecosystem, as they do in the open-access case. Instead they also depend on the changes of stocks over time. There-

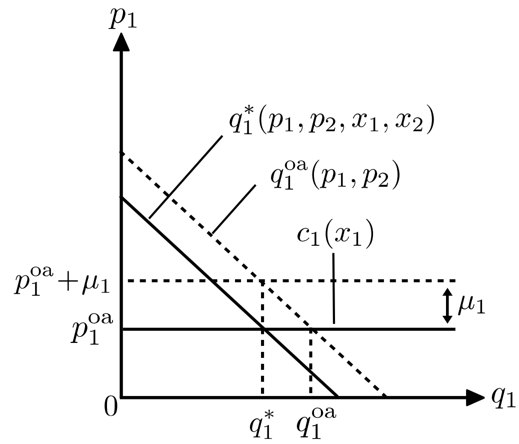

Figure 6.4: Market equilibrium for Species 1 with socially optimal demand and shadow prices.

fore, determining optimal harvest rates in this way necessarily takes into account all three avenues of interaction between species. Ecosystem interactions are included through the time derivatives of stocks. They are needed to correctly incorporate the ability of the ecosystem stock to recover from human impacts through harvesting. Technological interactions determine how species are harvested, as in the open-access case. Demand side interaction between species are given by the household preferences.

$$W = \max_{\vec{q}, y} \int_0^T U(\vec{q}, y)\ \mathrm{e}^{{}^t\rho t}\ \mathrm{d}t \tag{6.24}$$

Formally the optimal harvesting decision maker maximizes the time integral over the household utility function continuously discounted with discount rate ${}^t\rho$ subject to stock change (6.2) and per period budget constraints of households (6.14). In order to do this the decision maker chooses consumption levels of each of the species q_i and levels of other consumption y. Due to tractability issues of the model the socially optimised harvest rates are only determined for the steady states of the ecosystem, where harvests are exactly equal to the intrinsic growth of ecosystem stocks.

As in the open-access market equilibrium, technological interactions in harvesting limit the possible proportions of species in harvests and consumption. This limit stems from the supply side of the market being restricted by the the zero lower bound on fleet sizes (6.11). As a consequence the optimal equilibrium of the fish market has two cases depending on whether that condition is binding. In one case both gear types are available, and the manager may freely choose the species composition of harvests, in the other only one gear type is used and the manager is restricted to choosing the fleet size operating that gear. The resulting market equilibria for both cases are described below. The necessary derivations for each of the two cases are performed in Appendix 6.C of this paper. The condition for switching from the first case to the second is given by (6.25), which is derived in Appendix 6.C.3.

$$0 \geq \left(\sum_{i=1}^{\bar{i}} \left(\chi_i \nu_{i2}\right)^{\frac{\sigma-1}{\sigma}} \right)^{-1} \sum_{i''=1}^{\bar{i}} \left[\chi_{i''} \nu_{i''1} \left(\chi_{i''} \nu_{i''2}\right)^{\frac{\sigma-1}{\sigma}-1} \right] - \frac{\phi_1^{1-\epsilon} \sum_{i'=1}^{\bar{i}} \left[\mu_{i'} \chi_{i'} \nu_{i'1}\right]}{\phi_2^{1-\epsilon} \sum_{i'''=1}^{\bar{i}} \left[\mu_{i'''} \chi_{i'''} \nu_{i'''2}\right]} \tag{6.25}$$

The optimality measure described here only impacts the demand side of the model. It is assumed that harvesting firms behave as in the open-access case described above. Consequently, harvesting costs, determining prices in the first case, are equal to the open-access scenario.

Case 1: All Gear Types in Use in Optimal Harvesting

With all gear types in use, the socially optimal market equilibrium is characterised by the socially optimal demand function (6.26), with the possibility of freely setting species compositions in harvests. This function has an analogous structure to the household demand function shown in the previous section (6.15), derived in Blanz (2019). However, for each species a corresponding shadow price of stock depletion μ_i is added to the market prices p_i.

$$q_i = \alpha^{\eta} (p_i(\vec{x}) + \mu_i)^{-\sigma} \left(\sum_{i'=1}^{\bar{i}} (p_{i'}(\vec{x}) + \mu_{i'})^{1-\sigma} \right)^{\frac{\sigma-\eta}{1-\sigma}} \tag{6.26}$$

The shadow prices on stock depletion μ_i internalise the externalities caused by harvesting ecosystem stocks that are not included in the open-access scenario. They are determined depending on the stock growth equations $g_i(\vec{x})$ and the Jacobian of stock growth $\boldsymbol{J}(\vec{g}(\vec{x}))$ as well as price derivatives. The presence of the growth functions ensures that impacts from harvesting on the future prospects of each of the species is taken into account, while the cross derivatives are necessary to incorporate possible knock on effects from ecosystem interactions between species. The price derivatives incorporate changes in harvesting costs in the future due to current harvesting.

$$\vec{\mu} = \left({}^{t}\rho \boldsymbol{I}^{\bar{i}} - (\boldsymbol{J}(\vec{g}(\vec{x}))^{\intercal} \right)^{-1} \begin{pmatrix} -\frac{\partial p_1(\vec{x})}{\partial x_1} g_1(\vec{x}) \\ -\frac{\partial p_2(\vec{x})}{\partial x_2} g_2(\vec{x}) \end{pmatrix} \tag{6.27}$$

Prices (6.20) and fleet sizes (6.21) are determined identically to the open-access mode of the model. This is the case as inter-temporal consideration by the demand side of the market do not impact firm decision making or cost structures.

Regarding the importance of the different types of interaction between species, it is obvious from comparing the socially optimal solution for this case with that under open-access that ecosystem interactions now also need to be included. In the open-access scenario, they could safely be omitted. Technological interactions meanwhile again appear to play a significant role and therefore should not be omitted when determining optimal harvest rates. However, as in the scenario under open-access, for which conditions are given in Blanz (2019) and reproduced in the section above, conditions can be determined when such interaction or changes thereof do not change results. These are derived below. Demand side interactions meanwhile are present unconditionally.

Conditions for no Effect of Technological Interaction under Optimal Harvesting

In Blanz (2019) a chain of arguments regarding the simultaneous pressure on prices from adjusting the relative catch amounts of harvesting gear is used to motivate the derivation of the "conditions for no effect of bycatch". It remains to be shown that these conditions also hold for the setting with optimal harvesting rates. The starting point for the analogous argument chain is the welfare maximizing demand function for the case where both types of gear are in use (6.26). This function depends on shadow prices of stock depletion defined by (6.27) and prices. As a market equilibrium is assumed, prices are determined by harvesting costs (6.20). Given that harvesting costs are determined independently of the optimal harvesting rates, these are not different from the open-access case. Hence, the condition under which prices are independent of technological interaction (6.23) holds without change. Shadow prices depend on the direct derivatives of prices with respect to corresponding stocks multiplied by the inverse of the Jacobian of the growth function subtracted from the discount rate diagonal matrix. If the cross derivatives of the growth functions are zero, i.e. no ecosystem interaction between species is present, each shadow price only depends on the stock of a single corresponding species (6.28).

$$\mu_i = \left({}^t\rho - \frac{\partial g_i(\vec{x})}{\partial x_i} \right)^{-1} \left(-\frac{\partial p_i(x_i)}{\partial x_i} g_i(\vec{x}) \right) \tag{6.28}$$

Changing relative proportions of species in harvests using a certain gear type implies that total harvesting efficiency for that gear type remains constant. Consequently shadow prices μ_i will remain constant for different parametrisations of technological interaction in harvesting when the impact on shadow prices of changing relative harvesting efficiencies for one species is exactly equal to that on the other species. This is the case, as then only relative harvesting efficiencies are changed, an increase in one harvesting efficiency implies an equal decrease in the harvesting efficiency of the other species.

$$\frac{\mathrm{d}\mu_i}{\mathrm{d}\nu_{1k}} = \frac{\mathrm{d}\mu_i}{\mathrm{d}\nu_{2k}} \quad i \in I \quad k \in K \tag{6.29}$$

This simplifies to the same condition under which technological interaction in harvests has no effect on prices in the open-access setting (6.23). Thereby it is shown that the similar conditions for no effect of technological interaction apply under open-access and optimal harvesting. The only difference is the added requirement on ecosystem interaction in the case of optimal harvesting. The steps of the simplification can be found in Appendix 6.C.4.

Given these conditions, only when fleet composition can change freely and is of no concern to the modeller or manager, ecosystem interaction is not an issue and harvesting efficiencies and costs obey condition (6.23) may technological interaction between species be disregarded.

Case 2: One Gear Type Used in Optimal Harvesting

When the zero lower bound on fleet sizes (6.11) is binding, optimal harvesting rates are limited to determining the size of the single active fleet, analogous to the restricted open access case. In addition to the parameters and properties defining contemporary harvesting choices, optimal harvest rates also depend on the shadow prices of stock depletion μ_i.

$$n_k = \alpha^{\eta} \left(c_k + \sum_{i'=1}^{\bar{i}} \mu_{i'} h_{i'k}(x_i) \right)^{-\eta} \left(\sum_{i=1}^{\bar{i}} (h_{ik}(x_i) n_k)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{(\eta-1)\sigma}{\sigma-1}} \tag{6.30}$$

Shadow prices on stock depletion in this case depend on the discount rate ${}^{t}\rho$, growth equations, their derivatives and stock dependent harvesting efficiency. If ecosystem interactions between species are present, shadow prices further depend on the cross derivatives of the stock growth equations.

$$\vec{\mu} = {}^{\mu}A^{-1}\, {}^{\mu}\vec{b} \quad {}^{\mu}A(\vec{x}) \in \mathbb{R}^{\bar{i}\times\bar{i}} \quad {}^{\mu}\vec{b}(\vec{x}) \in \mathbb{R}^{\bar{i}} \quad \vec{\mu} \in \mathbb{R}^{\bar{i}} \tag{6.31}$$

$$\begin{aligned}
{}^{\mu}a_{ii} &= {}^{t}\rho + g_i(\vec{x}) \frac{\partial \chi_i}{\partial x_i} \chi_i^{-1} - \frac{\partial g_i(\vec{x})}{\partial x_i} \\
{}^{\mu}a_{ii'} &= -\frac{\partial g_{i'}(\vec{x})}{\partial x_i} \qquad i \neq i' \\
{}^{\mu}b_i &= \alpha \left(\sum_{i''=1}^{\bar{i}} (g_{i''}(\vec{x}))^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} (g_i(\vec{x}))^{\frac{\sigma-1}{\sigma}} \frac{\partial \chi_i}{\partial x_i} \chi_i^{-1}
\end{aligned}$$

Prices are then determined according to the inverse household demand function (6.16) and quantities of individual species according to total harvesting equation (6.5).

6.3 Management Implementation

Depending on how optimal harvesting rates are defined and implemented and how well they are enforced, species interaction effects may cause actual harvesting rates to deviate from those the manager is trying to achieve. In the context of this paper, the goal of management is to achieve the optimal steady state harvest rates determined in the previous section. I investigate three methods of implementing managed harvesting rates. Two are intended to represent management measures used in reality and one is a theoretical benchmark against which effectiveness of management can be measured. The benchmark is provided by a scenario with perfect control. In the two more realistic scenarios, harvesting is influenced through Total Allowable Catch (TAC) landing quotas and quantity based taxation, respectively. Under perfect control the socially optimal demand function replaces that of the representative household, ensuring the optimal outcome. This is considered to be the baseline optimal case against which the effectiveness of the other implementations is compared, with regards to harvesting rates, stock levels, consumption levels and consumer utility. The total allowable catch regulation is modelled as limiting the quantities harvested to those determined by the manager, whereas in the taxation scenario a tax rate set by the manager to mirror social costs of harvesting is added to prices, in order to internalise the social costs of stock change in the market equilibrium. Both of these scenarios are modelled by utilizing the short term demand function derived from household preferences (6.15) and modifying harvest rates or prices.

For the two realistic scenarios incentives for deviation from the intended harvest rates and discarding are analysed. I will show that the main difficulties in ensuring harvest rates matching those intended by the manager are caused by technological and demand side interactions. Ecosystem interactions, if they are known and taken into account by the manager, are not an issue in the context of compliance.

In analysing the consequences of the three types of interaction discussed in this paper, I focus especially on technological interaction. To this end, I also investigate the consequences of misspecifying the degree of technological interaction in harvesting for the effectiveness of the management measures mentioned above. Misspecification includes the possibility of assuming wrong relative proportions of harvesting efficiencies or disregarding technological interaction completely.

6.3.1 Perfect Control

In the case of perfect control the household is replaced by the manager as the demand side of the market. All household consumption decisions are then determined in such a way as to maximize long term welfare as opposed to short term utility. This implies that it is possible to reach any desired steady state of the ecosystem through determining harvesting rates appropriately. The transition period from any initial stocks before management comes into effect can not considered here as tractability of the model does not allow determining harvest rates during this period.

Long term welfare may require harvest rates on the boundary of the feasible species compositions in harvesting, even while demand according to short term utility consideration would determine harvest rates to be strictly within that space. In the case of perfect control this is not an issue, however under the more realistic management schemes described below this may cause deviation from the intended harvest rates.

6.3.2 Total Allowable Catch Quotas

One of the simplest measures in order to limit harvest rates to those set by the manager is to implement total allowable catch quotas (TAC) that apply industry wide for all fishing efforts. In the context of the model this implies exogenously forcing harvested quantities to be equal to those selected by the manager. As can easily be seen from Figure 6.4 together with Figure 6.3 this would lead to the market clearing condition (6.10) being violated. If that is the case, prices are no longer fully determined given the quantities consumed, as minimum harvesting costs will be lower than the willingness to pay by consumers. Nonetheless, this management method is attractive to managers as it appears to have comparatively low informational requirements. Harvest rates and corresponding ecosystem impacts can seemingly be set independently of the cost structure of harvesting firms and knowledge of catch rates of individual species and the technological interaction involved. However, in order for the ecosystem impact to be limited to that allowed by the TAC, harvesters may not discard parts of their catch while at sea. This is an issue whenever harvesting is not sufficiently selective, or in the terms of this paper when technological interaction in harvesting is high, and the TAC are not within the feasible harvesting space. In this case the fishers have an incentive to change the species composition of their catch to fit that of the TAC, by discarding catch of an individual species. Thereby landings will be in compliance with the TAC, while the total impact on the ecosystem, measured in fisheries induced mortality on ecosystem stocks, will be higher.

The potential ecosystem impact caused by this behaviour can be determined from the tool specific harvesting equations (6.6). The first step is to determine if the TAC amounts lie within the feasible set of harvesting. Only if this is not the case, does the incentive to discard while complying with the TAC exist in the way described above.

$$\frac{h_{ik'}(x_i)}{h_{i'k'}(x_{i'})} < \frac{q_i^{\mathrm{TAC}}}{q_{i'}^{\mathrm{TAC}}} < \frac{h_{ik}(x_i)}{h_{i'k}(x_{i'})} \tag{6.32}$$

When this condition (6.32) does not hold, potential mortality from TAC compliant landed harvests are calculated by plugging in the effort and fleet size needed to catch one of the species at the TAC quantity into the harvesting equation for the other, thereby determining the simultaneous catch amounts of the other species. The difference between catch amounts and TAC give the amount of discarded fish.

For the following analysis let species and gear types be indexed such that species i is prescribed to be caught in a greater proportion than i' and that only gear type k would be used in harvesting

$$\frac{h_{ik}(x_i)}{h_{i'k}(x_{i'})} < \frac{q_i^{\text{TAC}}}{q_{i'}^{\text{TAC}}} \tag{6.33}$$

then the quantities harvested of species i' will be in accordance with the TAC $h_{i'k}^{\text{TAC}}(x_{i'}) = q_{i'}^{\text{TAC}}$, while species i will be caught in greater amounts $h_{ik}^{\text{TAC}}(x_i) > q_i^{\text{TAC}}$ and discarded as needed to meet the TAC. The derivation of the simultaneous harvest rates satisfying the TAC for one of the species are shown in Appendix 6.D.

$$h_{ik}^{\text{TAC}}(x_i) = q_{i'}^{\text{TAC}} \frac{\nu_{ik}\chi_i}{\nu_{i'k}\chi_{i'}} \tag{6.34}$$

Total mortality for both species is equal to the calculated harvest rates $h_{ik}^{\text{TAC}}(x_i)$ and $h_{i'k}^{\text{TAC}}(x_{i'})$, respectively. Discards d_i of species i are given by the difference between q_i^{TAC} and $h_{ik}(x_i)$.

$$d_i = q_i^{\text{TAC}} - h_{ik}^{\text{TAC}}(x_i) \tag{6.35}$$

Increased mortality due to discarding can theoretically be avoided by a discard ban. With this in effect, harvesting would be shut down completely whenever the quantities caught of one of the species is equal to the TAC. Consequently harvests of the other species will be lower than that allowed by the TAC. These harvests can also be calculated using equation (6.34) above, by simply switching the indexing of the two species considered such that the direction of the inequality (6.33) is reversed. In that case harvest of the species not equal to TAC would be lower than prescribed $h_{ik}^{\text{TAC}}(x_i) < q_i^{\text{TAC}}$. The amount of under-harvesting of that species would then be obtained as the difference between TAC and actual harvest, analogous to the over-harvesting induced increased mortality. However, while monitoring of fleet wide discarding behaviour is possible, enforcing a discard ban is not cheap and may be prohibitively expensive (e.g. Sutinen and Andersen (1985); Daan (1997); Da Rocha et al. (2012)). Enforcement is especially costly as the action to be controlled occurs on each individual vessel while at sea. Furthermore, catch rates are stochastic and composition of individual catches may vary even without any discarding taking place, making enforcement of species composition in landings impractical.

This incentive for discarding can be avoided if TAC are set so that they are within the feasible set of harvesting rates, given the gear types available. Hence, while the attractiveness of this management measure rests in part on the idea that it requires no information about harvesting technology, the arguments in this section show that technological interaction needs to be taken into account, unless effective enforcement of a discard ban can be ensured. The other two types of interaction between species considered in this paper have no direct bearing on the effectiveness of this management measure. However, they are crucial in determining the TAC levels themselves. Disregarding ecosystem interaction in determining TAC would have obvious and well documented negative consequences for the impacted species, as described in the introduction. Whether consumer demand interactions between species matter partly depends on the goal of the manager. If the goal is simply to ensure a certain ecosystem state, the technological interaction may even yield an over-achievement of the goal, assuming lower harvests of one species due to an enforced discard ban. But even in such a case, where the goal is not to maximize welfare, consumer preferences matter as it is likely that choosing TACs that are not welfare maximizing do not provide harvested quantities in the same proportions as society demands. Furthermore, TACs may be too high or too low compared to the socially optimised harvest rates depending on the social discount rate ${}^{t}\rho$ and that implicitly assumed by the manager.

A benefit of TAC in comparison to tax based management, described below, is that it is comparatively robust with regards to misspecified technological interaction in harvesting, as long as the TAC are within the actual feasible set or enforcement of a discard ban can be achieved. If these conditions are met, even with a misspecified management quantities will equal the intended amounts. Under tax based management, the harvested amounts will deviate in such a situation with a high likelihood.

However, even if quantities are determined in an optimal manner and lie within the feasible set, the issue of the goods market clearing condition being violated still remains. Given that the TAC will not be equal to the market equilibrium, prices become undefined within the range between minimum harvesting costs and those appropriate to the quantities defined by the TAC. This can be seen in Figure 6.4 if q_1^* is taken to be the TAC.

Households would be willing to pay $p_1 + \mu_1$ while harvesting costs would remain at p_1. In this case fishers may achieve positive profits by increasing prices above the minimum harvesting costs. Alternatively, consumers could reap additional surplus by keeping prices at the minimum harvesting costs. In the first case the efficiency of the market equilibrium, ensuring that only the minimum required resources are used in fishing, would be lost. The second case would would be equal to the optimal result under direct control. The final result could be either of these outcomes or a combination of both, depending on the relative market power of consumers and fishers.

6.3.3 Quantity Based Taxes

Taxes based on harvested quantities either in the production or the consumption of fish may either cause a downward shift in the demand curve, implying that for any given price less fish will be demanded, or an upward shift in the supply curve, implying that any quantity of fish will become more expensive. In both cases the result is the same: The equilibrium quantity of the market will decrease. Ideally, the new quantities are equal to the socially optimal harvest rates. If tax revenue is then returned to households in the form of lump sum transfer allowing additional consumption of the manufactured good, the optimal result will be achieved.

Taxes intended to shift the market equilibrium into the the social optimum from a socially suboptimal market outcome are typically called pigouvian taxes (Pigou, 1920). The socially optimal outcome is obtained within the market by internalising any market externalities. The externality stemming from fisheries is the reduction of stocks available to the future. Current harvests have an impact on social welfare in addition to the direct benefit from consumption, as welfare also includes changes in future consumption due to reduced stocks. This impact is neither included in harvesting costs nor consumer demand. The magnitude of this externality on welfare is determined as part of the derivation of the socially optimal harvest rates (Section 6.2.6) and is represented by the shadow prices on stock depletion $\vec{\mu}$. If harvested quantities are taxed at a rate equal to these shadow prices, tax based management will achieve the same harvested quantities as under perfect control or TAC based management with optimally set quantities. In this section I will investigate the importance of the three possible types of interactions between species for tax based management.

As in the case of management by setting total allowable catch (TAC) quantities, taking ecosystem interactions into account is necessary in order for the harvest rates intended by management to be appropriate. This is the case as shadow prices of stock depletion (6.27) and (6.31) depend on the stock growth functions of all species impacted by harvesting. Simultaneously, technological interaction needs to be taken into account, as shadow prices also depend on the changes in future harvesting costs from stock change. Demand side interactions, meanwhile, need to be taken into account when setting taxes, as they determine how consumer demand will react to the increased prices. This is especially apparent in the cases where market demand limits harvesting to one gear type. In this case the optimal tax rates also depend on the parameters governing substitution between species σ, price elasticity of fish consumption η and overall relative importance of fish in consumption α. This is ensures that the changing net prices do not change the species composition of demand. If these properties of consumer preferences are not taken into account, substitution between species in consumption may shift harvest composition into the range where both gear types are used to harvest. As a consequence harvesting costs would change, impacting prices. Depending on the strength of this price adjustment the new harvest rates may be higher than those intended by management. This market adjustment would occur only after taxes had come in effect. Hence, it would not be correctly anticipated by a manager ignoring demand side interactions.

Comparing tax based management to TAC regulation, misspecification of technological interaction in harvesting or interaction between species in consumption will have a direct effect on harvested quantities, due changes in prices and corresponding substitution behaviour by consumers caused by such a misspecification. However, where fisheries may operate at inefficient levels under TAC quotas, tax based management ensures that all harvesting is performed with average cost minimizing effort levels. This is the case, since taxes to not create a wedge between supply and demand on the market for fish, but shift one of the curves, depending on where the tax is applied, in order to move the market equilibrium to a socially desirable location. If the goal of management is to set harvest rates at the socially optimal levels, both types of management have the same information requirements. However, when the goal of management is merely to set harvest rates ensuring that exogenous ecosystem targets are met, the informational costs necessary to set taxes are far greater than those needed to set TAC for the same goal.

6.4 Results and Discussion: Which Types of Interaction Matter

Using the model and the market equilibria derived it is possible to give an answer to the question posed in the introduction of this paper, which of the three types of interaction between species, ecosystem interaction, technological harvesting in harvesting and demand side interaction from consumer preferences necessarily have to be considered when managing multi-species fisheries. The answer to this question is motivated by considering when omitting some or all of these interaction types will impact effectiveness of management measures in achieving their intended goals. In short, the answer for all three types of interaction is "it depends". In the case of ecosystem interactions it depends on the time horizon of the decision maker. In the case of technological interactions it depends on the presence of ecosystem interactions, harvesting properties and the goal of management. In the case of demand side interactions it depends on the goal and stringency of management. The reasoning behind each of these answers as well as a more detailed explanation of the inter-dependencies between each of these interactions between species is given in the respective sections below.

6.4.1 Ecosystem Interaction

Interactions between species imply that the growth of an individual species depends not only on the ability of that species to reproduce, described by its ecosystem parameters, but also on the presence of other species in the ecosystem. Regardless of the specifics of this interaction, the simple property that growth is not independent of the species under consideration implies that the cross-derivatives of the stock growth function of the individual species with respect to other species must not be zero.

$$\frac{g_i(\vec{x})}{x_i'} \neq 0 \quad i \neq i' \quad i, i' \in I \tag{6.4}$$

Whenever these cross-derivatives are present in the solutions of the model and condition (6.4) holds, ecosystem interaction needs to be taken into account when determining harvesting rates. For the optimal harvesting solution the cross derivatives are present in the shadow prices of stock depletion (6.27) and (6.31) as part of the Jacobian of the stock growth functions. Only for management with a very short time horizon, approximated by the open-access solution of the model, stock growth is not considered at all and neither are its cross derivatives. Hence, ecosystem interactions have to be taken into account for any type of management deserving of the name.

In the context of the market for fish products, harvesting induced stock changes, with or without ecosystem interaction, can be considered as externalities to the market. Stock change is directly impacted by market interactions through the fishers' production function. The direct effect from this impact is reflected in household utility through consumption, but the indirect impact on social welfare through decreased future harvesting potential is not included. This decreased future harvesting potential critically depends on the ecosystem growth functions. Hence, any management internalising the effect of stock change, needs to include all components of stock change, including ecosystem interactions. As the laissez-faire type of management, i.e. open-access, does not internalise any part of the externality, it does not depend ecosystem interactions.

6.4.2 Technological Interaction

The case of technological interaction in the harvesting of species is simultaneously simpler and more complex than that of ecosystem interaction. It is conceptually simpler, in the context of the market for fish products, as it is included in the production and thereby directly included in prices. It does therefore not require to be internalised by management measures in order to be present in the market equilibria. However, even though it is present irrespective of the management type, it does not necessarily have an impact on outcomes. This implies that in the cases where it does not, it can safely be ignored. Conditions for this to be the case are derived for optimal harvesting in Section 6.2.6.

Technological interaction is represented in the model through the elements off the diagonal of the gear harvesting efficiency matrix ν (the diagonal elements give the harvesting efficiency for the target species of each gear type). The presence of such interaction is therefore modelled by these elements being different from zero.

$$\nu_{ik} \neq 0 \quad i \neq k \quad i \in I \quad k \in K \tag{6.36}$$

The conditions determining when this type of interaction can be safely omitted from modelling and management consideration are fourfold and need to be satisfied simultaneously. 1. Fleet composition can change freely and is not considered by management. 2. Ecosystem interactions between species are not an issue. 3. Relative costs and harvesting efficiencies satisfy the condition determining independence of prices from changes in relative harvesting efficiencies (6.23). 4. total harvesting efficiency over all species using a specific gear type is not changed. The first condition is required, as in order for technological interactions in harvests to have no effect on ecosystem stocks, fleet sizes need to be able to compensate the per vessel harvest amounts. In order for this compensation to be perfect, the third condition must also be met. Furthermore, fleet sizes will not be able to adjust, if they are restricted by the zero lower bound (6.11). There are two possibilities for the second condition to be satisfied. Either the ecosystem does not include species interaction or management is of the laissez-faire type, implying that ecosystem interaction is ignored even if it is present. The last two conditions are related to the first, as they depend on the parameters that govern how fleet size responds to different degrees of technological interaction. If these parameters are such that minimum harvesting costs of all species do not change, (6.23) is satisfied, fleet sizes adjust such that total harvests do not depend on the degree of interaction between species in harvests. The reasoning why it is sufficient for prices to remain unchanged in order to safely disregard technological interaction in harvesting is given by the following chain of arguments: From the consumer demand function (6.15) (and its socially optimal analogue (6.26)) it is obvious that if prices (and shadow prices) do not change, neither does the consumed quantity of fish products. If the quantities consumed do not change, neither does total harvest, due to assumed perfect markets implying that nothing is wasted and so the goods market clearing condition (6.10) holds. Finally, if total harvests do not change, neither do stock levels.

Outside of these rather narrow conditions for irrelevance of technological interactions in harvests for management. The goals of management may give further reason why a modeller may choose to omit this type of interaction. If management only considered ecosystem properties and determines harvested quantities as the maximum tolerable impact on the ecosystem from harvesting, the exact harvesting properties would also appear irrelevant. However if these harvest rates are infeasible given the available harvesting gear harvesters have a strong incentive to deviate from these harvest rates. This effect is described in Section 6.3 above for implementation through total allowable catch quotas (TAC).

6.4.3 Demand Side Interaction

When the goal of management is to maximize welfare, consumer preferences are a key determinant of harvest rates. If the preferences indicate a dependence of the utility from consuming one species on the consumption level of another, ignoring this would lead to harvesting rates that do not maximize welfare. However, if the management of the ecosystem aims to achieve not maximal welfare but other goals, such as maintaining stocks above certain specific ecological thresholds, it would appear that consumer preferences may be disregarded. However, through their role in determining demand for harvested species consumer preferences have further impact regarding the compliance with management measures.

They are therefore especially important when implementing taxes. Taxes change the net prices consumers face, hence if taxes are not set appropriately, the substitution behaviour they induce may cause harvests of other species to increase disproportionately. This effect is shown by Quaas and Requate (2013) for a scenario without ecosystem or technological interaction. They demonstrate a case where an otherwise healthy and sustainably harvested species is over-fished due to management imposed on other species in the ecosystem, ignoring the substitution effects in consumption.

In the case of management implemented by total allowable catch quotas, demand side interactions between species drive incentives for fishers to discard parts of their catch increasing mortality in the ecosystem beyond that intended by the manager.

6.4.4 Limitations and Outlook

While the aim of the model used for the analysis in this paper is to be general, it does have a number of limitations in its applicability. The strongest limitation is that it only includes two species and gear types. While it is argued that this is sufficient in order to reflect a wide range of possible interactions between species, this is not shown conclusively. A further limitation is the omission of non-use ecosystem properties which may also be impacted by harvesting activities and relevant to welfare but are not marketed or consumed. A third limitation of the model stems from its generality. As ecosystem processes are represented quite simplistically, it is possible that further feedback effects between ecosystem growth functions and the interactions discussed exist and were mistakenly assumed to be negligible. However, this is seen as a necessary trade-off in order to keep the model tractable. Furthermore, discarding rates are not included in the fishers' choices. Hence, while the incentives for discarding stemming from setting harvesting quotas incompatible with the harvesting technology can be discussed using the model, incentives due to variance in prices can not be analysed precisely.

These limitations motivate further work in improving the model. An extension to the case with arbitrary amounts of ecosystem species and harvesting gear types will allow analysis of further ecosystem and technological interactions. This would also be the first step in incorporating non-use ecosystem services, which could provide useful results on the interactions between non-harvested and harvested ecosystem components stemming from consumer demand. The analysis of fishers incentives regarding discarding can be improved by incorporating costly discarding within the fisher's profit function. Thereby the endogenous rate of discarding, chosen by fishers given market prices, can be determined. Furthermore this will allow determining the shadow price on limited discarding, i.e. when a ban is in effect. This shadow price gives the incentive of the fisher to violate the discard ban. However, while these improvements to the model will allow derivation of new results, it is not expected that they will negate those presented above.

6.5 Conclusion

Interactions between different managed species, be they directly within the ecosystem, through harvesting or from consumer demand, have significant effects for the determination of optimal harvesting rules. While ecosystem interactions between species are almost trivially important in setting optimal harvesting quotas, the significance of the other types of interaction is less obvious. Depending on the goals of the manager and their specific properties they may be omitted.

Using an analytical model including all of the three types of interaction between species, ecosystem interaction, technological interaction and demand side interaction, I derived socially optimal harvest rates in order to show their dependence on each of these three types of interaction. I further investigated total allowable catch quotas (TAC) and quantity based taxes as management measures to enforce the socially optimal harvesting rates under market demand and supply derived for the open-access setting. Regarding the derived socially optimal harvesting rates, I found that ecosystem interactions can not be omitted when setting harvest rates, technological interactions in harvesting may be omitted in specific cases and demand side interactions may not be omitted. For the different management implementations of harvesting rates I found that their effectiveness strongly depends on technological and consumer demand interactions. In the case of TAC regulation technological interaction in harvesting was found to be especially important in determining the incentives of harvesters to discard parts of their catch, increasing mortality beyond that intended by management. For implementation of successful tax based management, meanwhile, knowledge of consumer substitution behaviour due to changes in net prices was shown to be essential. As a consequence, even in cases where one might assume that it is not necessary to include technological or demand side interactions, as the goal of management is not to maximize societal welfare but simply to ensure certain levels of ecosystem stocks, omitting these interactions can undermine the effectiveness of management measures.

In light of these results it appears advisable to include all three types of interactions between managed species when modelling multi-species fisheries in order to better anticipate what would otherwise be classified as unforeseen behaviour of the human actors in the system.

Appendix

Appendices 6.A and 6.B determining the open-access behaviour of the model are reproductions from Blanz (2019) with some modifications, shown here in order to aid comparison of the open-access and socially optimal solutions of the model.

6.A The Firm Optimisation Problem

In the following, vector notation is used to simplify the equations. For this the following definition is needed.

$$\chi = \begin{pmatrix} \ddots & & 0 \\ & \chi_i & \\ 0 & & \ddots \end{pmatrix} \tag{6.37}$$

Furthermore as above the following abbreviation is used.

$$\chi_i = \chi(x_i) \tag{6.38}$$

The effort level is determined by maximizing profits.

$$e_k^{**} = \arg \max_{e_k} \vec{P}^\intercal \chi \vec{\nu}_k e_k^\epsilon - \omega e_k - \phi_k \tag{6.39}$$

The resulting first order condition is:

$$\epsilon \vec{P}^\intercal \chi \vec{\nu}_k e_k^{\epsilon-1} - \omega = 0 \tag{6.40}$$

Rearranging yields the optimal harvesting effort level per tool.

$$e_k^{**} = \left(\frac{\epsilon \vec{P}^\intercal \chi \vec{\nu}_k}{\omega} \right)^{\frac{1}{1-\epsilon}} \tag{6.41}$$

As perfect markets are assumed in the model, market pressure will drive profits to zero. These market processes are not observable in the model's results, as they are assumed to happen instantaneously and only the resulting market equilibrium is calculated.

The zero profit condition reads:

$$\vec{P}^{\intercal}\chi\vec{\nu}_k e_k^{\epsilon} - \omega e_k = \phi_k \tag{6.42}$$

Rearranging of (6.41) and substituting into a rearranged (6.42) yields the optimal market equilibrium effort level. Note that this does not imply an equilibrium in the ecosystem stock change, but merely an equilibrium in market entry and exit of harvesting firms.

$$\begin{aligned}
(6.41) \Leftrightarrow \quad && e_k^{1-\epsilon} &= \frac{\epsilon\vec{p}^{\intercal}\left(\vec{h}_k\chi\right)}{\omega} \\
(6.42) \Leftrightarrow \quad && \frac{\epsilon\vec{p}^{\intercal}\left(\vec{h}_k\chi\right)}{\omega}e_k^{\epsilon} - e_k\epsilon &= \frac{\phi_k}{\omega}\epsilon \\
\Leftrightarrow \quad && e_k(1-\epsilon) &= \frac{\phi_k}{\omega}\epsilon \\
\Leftrightarrow \quad && e_k^* &= \frac{\phi_k}{\omega}\frac{\epsilon}{1-\epsilon} && (6.43)
\end{aligned}$$

Optimal market-equilibrium effort decreases with wages. This is to be expected, as increasing wages imply that the firm can not afford as much labour. The model does not allow for substitution into variable capital. There is only fixed capital, covered by fixed costs. Furthermore, increasing fixed costs increases equilibrium effort level. This can be explained by increased fixed costs implying that more effort is needed to reach break-even. This ignores the possibility of not producing using a certain technology, however.

6.B The Household Optimisation Problem and Market Equilibria

6.B.1 All Tools In Use

In the case where no non–negativity conditions are binding, the household optimisation problem reads as follows:

$$\max_{Q,y} U(Q,y) \text{ s.t. } \omega = y + \sum_{i=1}^{\bar{i}} p_i q_i \tag{6.44}$$

The corresponding Lagrangian function:

$$\mathcal{L}(Q,y) = U(Q,y) - \lambda(\omega - y - \sum_{i=1}^{\bar{i}} p_i q_i) \tag{6.45}$$

The resulting first order conditions:

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}y} = 1 + \lambda \qquad = 0 \tag{6.46}$$

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}q_{i'}} = \alpha q_{i'}^{\frac{\sigma-1}{\sigma}-1} \left(\sum_{i=1}^{\bar{i}} q_i^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} + \lambda p_{i'} \qquad = 0 \tag{6.47}$$

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\lambda} = \omega - y - \sum_{i=1}^{\bar{i}} p_i q_i \qquad = 0 \tag{6.48}$$

From (6.46) it trivially follows that $\lambda = -1$. This can be used in (6.47), which can then be rearranged to find the demand function for each harvested species as follows.

$$
\begin{aligned}
(6.47) \Leftrightarrow \quad & \alpha q_{i'}^{\frac{\sigma-1}{\sigma}-1} \left(\sum_{i=1}^{\bar{i}} q_i^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} = p_{i'} \\
\Leftrightarrow \quad & \alpha q_{i'}^{\frac{\sigma-1}{\sigma}-1} Q^{\frac{\eta-1}{\eta}-\frac{\sigma-1}{\sigma}} = p_{i'} \qquad (6.49)\\
\Leftrightarrow \quad & \alpha q_{i'}^{-\frac{1}{\sigma}} Q^{\frac{\eta-1}{\eta}-\frac{\sigma-1}{\sigma}} = p_{i'} \qquad (6.50)\\
\Leftrightarrow \quad & \left(\alpha Q^{\frac{\eta-1}{\eta}-\frac{\sigma-1}{\sigma}} \right)^{1-\sigma} q_{i'}^{\frac{\sigma-1}{\sigma}} = p_{i'}^{1-\sigma} \\
\Leftrightarrow \quad & \left(\alpha Q^{\frac{\eta-1}{\eta}-\frac{\sigma-1}{\sigma}} \right)^{1-\sigma} \underbrace{\sum_{i'=1}^{\bar{i}} q_{i'}^{\frac{\sigma-1}{\sigma}}}_{Q^{\frac{\sigma-1}{\sigma}}} = \sum_{i'=1}^{\bar{i}} p_{i'}^{1-\sigma} \\
\Leftrightarrow \quad & \alpha^{1-\sigma} Q^{(1-\sigma)\left(\frac{1}{\eta}\right)} = \sum_{i'=1}^{\bar{i}} p_{i'}^{1-\sigma} \\
\Leftrightarrow \quad & \left(\alpha Q^{\frac{1}{\eta}} \right)^{1-\sigma} = \sum_{i'=1}^{\bar{i}} p_{i'}^{1-\sigma} \\
\Leftrightarrow \quad & \alpha Q^{\frac{1}{\eta}} = \underbrace{\left(\sum_{i'=1}^{\bar{i}} p_{i'}^{1-\sigma} \right)^{\frac{1}{1-\sigma}}}_{P} \\
\Leftrightarrow \quad & Q = \alpha^{\eta} P^{-\eta} \qquad (6.51)
\end{aligned}
$$

Hereby a price index P is used.

$$
P = \left(\sum_{i'=1}^{\bar{i}} p_{i'}^{1-\sigma} \right)^{\frac{1}{1-\sigma}} \qquad (6.52)
$$

(6.51) can itself be substituted into (6.49) to finally obtain the demand function (6.53).

$$
\begin{aligned}
(6.49) \Leftrightarrow \quad & \alpha q_i^{\frac{1}{\sigma}} \left(\alpha^{\eta} P^{-\eta} \right)^{\frac{\eta-1}{\eta}-\frac{\sigma-1}{\sigma}} = p_i \\
\Leftrightarrow \quad & q_i = \alpha^{\eta} p_i^{-\sigma} P^{\sigma-\eta} \\
\Leftrightarrow \quad & q_i = \alpha^{\eta} p_i^{-\sigma} \left(\sum_{i'=1}^{\bar{i}} p_{i'}^{1-\sigma} \right)^{\frac{\sigma-\eta}{1-\sigma}} \qquad (6.53)
\end{aligned}
$$

6.B.2 Prices, All Tools In Use

Given the assumption that $\bar{i} = \bar{k}$ and the zero profit condition, prices are equal to unit costs in production. These are determined by solving the zero profit conditions of all $\bar{k}$ tools simultaneously.

First the optimal effort level satisfying the individual zero profit conditions (6.43) is plugged back into the respective zero profit conditions.

$$\underbrace{\vec{p}'\chi\vec{\nu}_k\Bigg(\overbrace{\frac{\phi_k}{\omega}\frac{\epsilon}{1-\epsilon}}^{e_k^*}\Bigg)^{\epsilon}}_{\text{revenue}} = \underbrace{\omega\overbrace{\frac{\phi_k}{\omega}\frac{\epsilon}{1-\epsilon}}^{e_k^*}}_{\text{wage costs}} + \underbrace{\phi_k}_{\text{fixed costs}}$$

$$\Leftrightarrow \quad \vec{p}'\chi\vec{\nu}_k\left(\frac{\phi_k}{\omega}\frac{\epsilon}{1-\epsilon}\right)^{\epsilon} = \phi_k\left(1+\frac{\epsilon}{1-\epsilon}\right)$$

$$\Leftrightarrow \quad \vec{p}'\chi\vec{\nu}_k = \phi_k\left(1+\frac{\epsilon}{1-\epsilon}\right)\left(\frac{\phi_k}{\omega}\frac{\epsilon}{1-\epsilon}\right)^{-\epsilon} \tag{6.54}$$

Equation (6.54) above represents a system of $\bar{k}$ linear equations. This can be used to determine the $\bar{i}$ prices p_i. However, this requires that $\bar{k} = \bar{i}$. Writing out the vector multiplications makes the linearity more easily apparent.

$$(6.54) \Leftrightarrow \sum_{i=1}^{\bar{i}} p_i\chi_i(\vec{x})\nu_{ik} = \underbrace{\phi_k\left(1+\frac{\epsilon}{1-\epsilon}\right)\left(\frac{\phi_k}{\omega}\frac{\epsilon}{1-\epsilon}\right)^{-\epsilon}}_{{}^{p}b_k} \tag{6.55}$$

To solve the system, it is rearranged as follows:

$${}^{p}A\;\vec{p} = {}^{p}\vec{b} \tag{6.56}$$

The top left index is used to denote that this LSE (linear system of equations) is used to solve for prices, as opposed to the LSE used to determine the number of firms below.

$$
\begin{aligned}
{}^{p}A &= \nu^{\intercal}\chi && (6.57)\\
{}^{p}\vec{b} &= \begin{pmatrix} {}^{p}b_1 \\ \vdots \\ {}^{p}b_{\bar{k}} \end{pmatrix} && (6.58)\\
{}^{p}b_k &= \phi_k\left(1+\frac{\epsilon}{1-\epsilon}\right)\left(\frac{\phi_k}{\omega}\frac{\epsilon}{1-\epsilon}\right)^{-\epsilon} && (6.59)
\end{aligned}
$$

Prices can then be easily solved for.

$$
\begin{aligned}
\vec{p} &= {}^{p}A^{-1}\,{}^{p}\vec{b} && (6.60)\\
&= \chi^{-1}(\nu^{\intercal})^{-1}\,{}^{p}\vec{b}
\end{aligned}
$$

Thereby prices are fully determined.

6.B.3 Number of Firms, All Tools in Use

Starting from the goods market clearing conditions for each of the species the problem of determining the numbers of firms can be transformed into a system of linear equations and solved as such.

$$
\begin{aligned}
& & H_i &= q_i(\vec{p})\\
&\Leftrightarrow & \sum_{k=1}^{\bar{k}} n_k\chi(x_i)\nu_{ik}e_k^{*\epsilon} &= q_i(\vec{p})\\
&\Leftrightarrow & \frac{q_i(\vec{p})}{\chi(x_i)} &= \sum_{k=1}^{\bar{k}} n_k\nu_{ik}e_k^{*\epsilon} && (6.61)
\end{aligned}
$$

Represented as a LSE:

$$
{}^{n}A\,\vec{n} = {}^{n}\vec{b} \tag{6.62}
$$

with

$$^{n}A = \nu \;\; \mathrm{diag}(\vec{e^{*\epsilon}})$$

and

$$\begin{aligned} {}^{n}\vec{b} &= \chi^{-1}(\vec{x}) \; \vec{q}(\vec{p}) \\ \Leftrightarrow \qquad {}^{n}b_i &= \chi^{-1}(x_i) \; q_i(\vec{p}) \end{aligned}$$

.

Solving for n yields:

$$\vec{n} = {}^{n}A^{-1} \;\; {}^{n}\vec{b} \tag{6.63}$$

6.B.4 One Tool in Use

In order to solve the household optimisation problem in this context, the Kuhn-Tucker conditions are used (Kuhn, 2014). To simplify the analysis the goods market clearing condition (6.10) is substituted into the sub-utility for fish (6.13) and the budget restriction is reformulated.

$$\tilde{Q} = \tilde{Q}(\vec{n}) = \left(\sum_{i=1}^{\bar{i}} \Bigg(\underbrace{\sum_{k=1}^{\bar{k}} n_k h_{ik}(x_i)}_{q_i} \Bigg)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \tag{6.64}$$

Hereby the c_k represents the operating costs of each firm of type k. The firm costs do not depend on any variables as it is assumed that firms operate at the zero-profit profit-maximizing level (6.9).

$$\begin{aligned} c_k &= e^*_k \omega + \phi_k \\ &= \phi_k \left(1 + \frac{\epsilon}{1-\epsilon} \right) \end{aligned} \tag{6.65}$$

Given that firms operate at the equilibrium level, the sum of costs multiplied with the number of firms must equal the sum of prices multiplied by consumed amounts of species.

$$\sum_{k=1}^{\bar{k}} c_k n_k = \sum_{i=1}^{\bar{i}} p_i q_i \tag{6.66}$$

This is substituted into (6.14) to yield the reformulated budget constraint.

$$y = \omega - \sum_{k=1}^{\bar{k}} c_k n_k \tag{6.67}$$

The representative household now chooses the type and number of bundles of fish in order to maximize utility. Bundles consist of certain amounts of each harvestable species. The composition of the bundles is defined by equilibrium output of a single firm of each type $h_k(\vec{x})$.

$$h_k(\vec{x}) = \begin{pmatrix} h_{1k}(x_1) \\ \vdots \\ h_{\bar{i}k}(x_{\bar{i}}) \end{pmatrix} \tag{6.68}$$

The Lagrangian of the household optimisation problem then is:

$$\mathcal{L}(\vec{n}) = \omega - \sum_{k=1}^{\bar{k}} c_k n_k + \alpha \frac{\eta}{\eta - 1} \left(\sum_{i=1}^{\bar{i}} \left(\sum_{k=1}^{\bar{k}} n_k h_{ik}(x_i) \right)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}} - \sum_{k=1}^{\bar{k}} \lambda_k(-n_k) \tag{6.69}$$

As $\ln(Q)$ is the continuous extension of $\frac{\eta}{\eta-1} Q^{\frac{\eta-1}{\eta}}$ the first order conditions derived using the above equation also extend to the case $\eta = 1$.

The first order conditions are:

$$\frac{\mathrm{d}\mathcal{L}(\vec{n})}{\mathrm{d}n_k} = 0 \tag{6.70}$$

$$\lambda_k \geq 0 \tag{6.71}$$

$$-n_k \leq 0 \tag{6.72}$$

$$-\lambda_k n_k = 0 \tag{6.73}$$

To determine the solution to the household optimisation problem, it is split into cases depending on the number of tool types in use. The cases considered are:

1. All tool types are in use
2. Only one tool type is in use
3. Not all tools are in use, but more than one is in use

In order to keep the analysis simple, for the remainder of this paper only two species and harvesting tools are considered. This removes the third case from consideration.

Assumption 5. $\bar{k} = \bar{i} = 2$

The demand for the bundle provided by the active firm is derived by using the fact that the number of active firms for all other tool types is zero, in the optimality conditions of the household optimisation problem. Let there exist a single tool type with positive active firms ($n_k > 0$) and let all other tool types have zero active firms ($n'_k = 0 \ \forall k \in \{[1, \bar{k}] \backslash k'\}$). From (6.73) it follows that $\lambda_k = 0$.

$$
\begin{aligned}
(6.70) \Leftrightarrow \qquad & 0 = \frac{\mathrm{d}\mathcal{L}(\vec{n}}{\mathrm{d}n_k} \\
\Leftrightarrow \qquad & 0 = \lambda_k - c_k + \alpha \left(\sum_{i=1}^{\bar{i}} \left(\sum_{k=1}^{\bar{k}} n_k h_{ik}(x_i) \right)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} \\
& \sum_{i=1}^{\bar{i}} h_{ik}(x_i) \left(\sum_{k=1}^{\bar{k}} n_k h_{ik}(x_i) \right)^{\frac{\sigma-1}{\sigma}-1}
\end{aligned}
$$

using $n_k' = 0$ and $\lambda_k = 0$

$$\Leftrightarrow \qquad 0 = 0 - c_k + \alpha\left(\sum_{i=1}^{\bar{i}} \big(n_k h_{ik}(x_i)\big)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} \sum_{i=1}^{\bar{i}} h_{ik}(x_i)\big(n_k h_{ik}(x_i)\big)^{\frac{\sigma-1}{\sigma}-1}$$

$$\Leftrightarrow \qquad 0 = -c_k + \alpha\left(\sum_{i=1}^{\bar{i}} \big(n_k h_{ik}(x_i)\big)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} \sum_{i=1}^{\bar{i}} h_{ik}(x_i)^{\frac{\sigma-1}{\sigma}} n_k^{\frac{\sigma-1}{\sigma}-1}$$

$$\Leftrightarrow \qquad 0 = -c_k + \alpha\left(\sum_{i=1}^{\bar{i}} n_k^{\frac{\sigma-1}{\sigma}} h_{ik}(x_i)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} n_k^{\frac{\sigma-1}{\sigma}-1} \sum_{i=1}^{\bar{i}} h_{ik}(x_i)^{\frac{\sigma-1}{\sigma}}$$

$$\Leftrightarrow \qquad 0 = -c_k + \alpha n_k^{\frac{\sigma-1}{\sigma}\left(\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1\right)} n_k^{\frac{\sigma-1}{\sigma}-1} \frac{\eta}{\eta-1}\left(\sum_{i=1}^{\bar{i}} h_{ik}(x_i)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1}$$
$$\sum_{i=1}^{\bar{i}} h_{ik}(x_i)^{\frac{\sigma-1}{\sigma}}$$

$$\Leftrightarrow \qquad 0 = -c_k + \alpha n_k^{-\frac{1}{\eta}}\left(\sum_{i=1}^{\bar{i}} h_{ik}(x_i)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}}$$

$$\Leftrightarrow \quad n_k^{-\frac{1}{\eta}} = c_k \alpha^{-1}\left(\sum_{i=1}^{\bar{i}} h_{ik}(x_i)^{\frac{\sigma-1}{\sigma}}\right)^{-\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}} \tag{6.74}$$

$$\Leftrightarrow \qquad n_k = c_k^{-\eta}\alpha^{\eta}\left(\sum_{i=1}^{\bar{i}} h_{ik}(x_i)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{(\eta-1)\sigma}{\sigma-1}} \tag{6.75}$$

Equation (6.75) relates the number of bundles of type k demanded by the household. The number of goods demanded by the household follows from the goods market clearing condition (6.10).

$$q_i = n_k h_{ik}(x_i)$$

$$q_i = c_k^{-\eta}\alpha^{\eta}\left(\sum_{i=1}^{\bar{i}} h_{ik}(x_i)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{(\eta-1)\sigma}{\sigma-1}} \nu_{ik} e_k^{*\epsilon} \chi_i$$

$$q_i = (e_k^*\omega + \phi_k)^{-\eta}\alpha^{\eta}\left(\sum_{i=1}^{\bar{i}} h_{ik}(x_i)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{(\eta-1)\sigma}{\sigma-1}} \nu_{ik} e_k^{*\epsilon} \chi_i \tag{6.76}$$

6.B.5 Condition for Only One Tool in Use

In the following the condition for single tool use is derived. Without loss of generality this is done for Tool 1. Given the assumption that $\bar{i} = \bar{k} = 2$ let $n_1 = 0$ and hence $\lambda_1 > 0$ while $n_2 > 0$ and $\lambda_2 = 0$.

Starting from (6.70) for Tool 1:

$$0 = \lambda_1 - c_1 + \alpha \left(\sum_{i=1}^{\bar{i}} \left(\sum_{k=1}^{\bar{k}} n_k h_{ik}(x_i) \right)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} \sum_{i=1}^{\bar{i}} \left[h_{i1}(x_i) \left(\sum_{k=1}^{\bar{k}} n_k h_{ik}(x_i) \right)^{\frac{\sigma-1}{\sigma}-1} \right]$$

Using the asssumption that $\bar{i} = \bar{k} = 2$ and assuming without loss of generality that $n_1 = 0$ and hence $\lambda_1 > 0$ while $n_2 > 0$ and $\lambda_2 = 0$.

$$\Rightarrow \quad 0 = \lambda_1 - c_1 + \alpha \left(\sum_{i=1}^{\bar{i}} \left(n_2 h_{i2}(x_i) \right)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} \sum_{i=1}^{\bar{i}} \left[h_{i1}(x_i) \left(n_2 h_{i2}(x_i) \right)^{\frac{\sigma-1}{\sigma}-1} \right]$$

$$\Leftrightarrow \quad -\lambda_1 = n_2^{\frac{\sigma-1}{\sigma}\left(\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1\right)} \alpha \left(\sum_{i=1}^{\bar{i}} h_{i2}(x_i)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} n_2^{\frac{\sigma-1}{\sigma}-1} \sum_{i=1}^{\bar{i}} \left[h_{i1}(x_i) h_{i2}(x_i)^{\frac{\sigma-1}{\sigma}-1} \right] - c_1$$

$$\Leftrightarrow \quad -\lambda_1 = n_2^{-\frac{1}{\eta}} \alpha \left(\sum_{i=1}^{\bar{i}} h_{i2}(x_i)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} \sum_{i=1}^{\bar{i}} \left[h_{i1}(x_i) h_{i2}(x_i)^{\frac{\sigma-1}{\sigma}-1} \right] - c_1$$

The factor $n_2^{1-\eta}$ can be substituted by (6.74), due to Assumption 5, I.e. because Tool 2 is the only tool used.

$$\Rightarrow \quad -\lambda_1 = \overbrace{c_2 \alpha^{-1} \left(\sum_{i=1}^{\bar{i}} h_{i2}(x_i)^{\frac{\sigma-1}{\sigma}} \right)^{-\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}}}^{n_2^{-\frac{1}{\eta}}} \alpha \left(\sum_{i=1}^{\bar{i}} h_{i2}(x_i)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} \sum_{i=1}^{\bar{i}} \left[h_{i1}(x_i) h_{i2}(x_i)^{\frac{\sigma-1}{\sigma}-1} \right] - c_1$$

$$\Leftrightarrow \quad -\lambda_1 = c_2 \left(\sum_{i=1}^{\bar{i}} h_{i2}(x_i)^{\frac{\sigma-1}{\sigma}} \right)^{-1} \sum_{i=1}^{\bar{i}} \left[h_{i1}(x_i) h_{i2}(x_i)^{\frac{\sigma-1}{\sigma}-1} \right] - c_1$$

Substitute (6.65) for c_k and equilibrium harvests obtained by plugging (6.9) in (6.6) for $h_{ik}(x_i)$.

$$\begin{aligned}
\Rightarrow\quad -\lambda_1 &= (\phi_2+\omega e_2^*)\left(\sum_{i=1}^{\bar{i}}(\chi_i\nu_{i2}e_2^*)^{\frac{\sigma-1}{\sigma}}\right)^{-1}\sum_{i=1}^{\bar{i}}\left[(\chi_i\nu_{i1}e_1^*)\,(\chi_i\nu_{i2}e_2^*)^{\frac{\sigma-1}{\sigma}-1}\right]-(\phi_1+\omega e_1^*)\\
\Leftrightarrow\quad -\lambda_1 &= (\phi_2+\omega e_2^*)\,e_2^{*\frac{1-\sigma}{\sigma}}\left(\sum_{i=1}^{\bar{i}}(\chi_i\nu_{i2})^{\frac{\sigma-1}{\sigma}}\right)^{-1} e_1^*e_2^{*\frac{\sigma-1}{\sigma}-1}\sum_{i=1}^{\bar{i}}\left[(\chi_i\nu_{i2})^{\frac{\sigma-1}{\sigma}}\frac{\nu_{i1}}{\nu_{i2}}\right]-\phi_1-\omega e_1^*\\
\Leftrightarrow\quad -\lambda_1 &= e_1^*\left(\frac{\phi_2}{e_2^*}+\omega\right)\left(\sum_{i=1}^{\bar{i}}(\chi_i\nu_{i2})^{\frac{\sigma-1}{\sigma}}\right)^{-1}\sum_{i=1}^{\bar{i}}\left[(\chi_i\nu_{i2})^{\frac{\sigma-1}{\sigma}}\frac{\nu_{i1}}{\nu_{i2}}\right]-\phi_1-\omega e_1^*
\end{aligned}$$

Substitute (6.9) for e_k^*.

$$\begin{aligned}
\Rightarrow\quad -\lambda_1 &= \left(\frac{\phi 1}{\omega}\frac{\epsilon}{1-\epsilon}\right)\left(\frac{\phi_2\omega}{\phi_2}\frac{1-\epsilon}{\epsilon}+\omega\right)\left(\sum_{i=1}^{\bar{i}}(\chi_i\nu_{i2})^{\frac{\sigma-1}{\sigma}}\right)^{-1}\sum_{i=1}^{\bar{i}}\left[(\chi_i\nu_{i2})^{\frac{\sigma-1}{\sigma}}\frac{\nu_{i1}}{\nu_{i2}}\right]\\
&\quad-\phi_1\left(1+\frac{\epsilon}{1-\epsilon}\right)\\
\Leftrightarrow\quad -\lambda_1 &= \underbrace{\phi_1\left(1+\frac{\epsilon}{1-\epsilon}\right)}_{c_1}\left(\sum_{i=1}^{\bar{i}}(\chi_i\nu_{i2})^{\frac{\sigma-1}{\sigma}}\right)^{-1}\sum_{i=1}^{\bar{i}}\left[(\chi_i\nu_{i2})^{\frac{\sigma-1}{\sigma}}\frac{\nu_{i1}}{\nu_{i2}}\right]\underbrace{-\phi_1\left(1+\frac{\epsilon}{1-\epsilon}\right)}_{-c_1}\\
\Leftrightarrow\quad -\lambda_1 &= c_1\left(\left(\sum_{i=1}^{\bar{i}}(\chi_i\nu_{i2})^{\frac{\sigma-1}{\sigma}}\right)^{-1}\sum_{i=1}^{\bar{i}}\left[(\chi_i\nu_{i2})^{\frac{\sigma-1}{\sigma}}\frac{\nu_{i1}}{\nu_{i2}}\right]-1\right)\\
\Leftrightarrow\quad -\lambda_1 &= c_1\left(\left(\sum_{i=1}^{\bar{i}}(\chi_i\nu_{i2})^{\frac{\sigma-1}{\sigma}}\right)^{-1}\left(\sum_{i=1}^{\bar{i}}\left[(\chi_i\nu_{i2})^{\frac{\sigma-1}{\sigma}}\frac{\nu_{i1}}{\nu_{i2}}\right]-\sum_{i=1}^{\bar{i}}(\chi_i\nu_{i2})^{\frac{\sigma-1}{\sigma}}\right)\right)\\
\Leftrightarrow\quad -\lambda_1 &= c_1\left(\sum_{i=1}^{\bar{i}}(\chi_i\nu_{i2})^{\frac{\sigma-1}{\sigma}}\right)^{-1}\left(\sum_{i=1}^{\bar{i}}(\chi_i\nu_{i2})^{\frac{\sigma-1}{\sigma}}\left(\frac{\nu_{i1}}{\nu_{i2}}-1\right)\right)
\end{aligned}\tag{6.77}$$

From (6.73) in conjunction with (6.77) it follows that

$$0\geq\sum_{i=1}^{\bar{i}}(\chi_i\nu_{i2})^{\frac{\sigma-1}{\sigma}}\left(\frac{\nu_{i1}}{\nu_{i2}}-1\right)\tag{6.78}$$

where the equality holds only if (6.72) is not binding. Conversely the condition for Tool 1 not being employed is:

$$0>\sum_{i=1}^{\bar{i}}(\chi_i\nu_{i2})^{\frac{\sigma-1}{\sigma}}\left(\frac{\nu_{i1}}{\nu_{i2}}-1\right)\tag{6.79}$$

6.B.6 Conditions For No Effect of Bycatch

Given assumption $\bar{i} = \bar{k} = 2$ (two species, two tools) the equation determining the prices (6.60) can be written, for the price of Species 1, in expanded form as

$$p_1(\nu) = (\chi_1\chi_2)^{-1}(\nu_{11}\nu_{22} - \nu_{12}\nu_{21})^{-1}(\chi_2\nu_{22}\,{}^{p}b_1 - \chi_2\nu_{21}\,{}^{p}b_2) \tag{6.80}$$

As it is only relevant whether the price changes, not how it changes, and as prices are directly related through the demand function, this derivation can without loss of generality be done only for the price of Species 1.

It is assumed that the sum of the total harvesting efficiency of the tools remains constant while adding bycatch to the model. For the price to remain constant the derivative of the price with respect to the increasing harvesting efficiency must equal the derivative with respect to the decreasing harvesting efficiency. Without loss of generality, let ν_{12} be the increasing and ν_{22} the decreasing harvesting efficiency.

$$\begin{aligned}
\frac{\mathrm{d}p_1}{\mathrm{d}\nu_{12}} &= \frac{\mathrm{d}p_1}{\mathrm{d}\nu_{22}} && (6.81)\\
\frac{\nu_{21}\left({}^{p}b_1\nu_{22} - {}^{p}b_2\nu_{21}\right)}{\left(\nu_{12}\nu_{21} - \nu_{11}\nu_{21}\right)^2\chi_1} &= \frac{\nu_{21}\left({}^{p}b_2\nu_{11} - {}^{p}b_1\nu_{12}\right)}{\left(\nu_{12}\nu_{21} - \nu_{11}\nu_{22}\right)^2\chi_1}\\
{}^{p}b_1\nu_{22} - {}^{p}b_2\nu_{21} &= {}^{p}b_2\nu_{11} - {}^{p}b_1\nu_{12}\\
{}^{p}b_1(\nu_{22} + \nu_{12}) &= {}^{p}b_2(\nu_{11} + \nu_{21})\\
\frac{{}^{p}b_1}{{}^{p}b_2} &= \frac{\nu_{11} + \nu_{21}}{\nu_{12} + \nu_{22}} && (6.82)
\end{aligned}$$

substitute ${}^{p}b$ with (6.59)

$$\begin{aligned}
\frac{\phi_1\left(1 + \frac{\epsilon}{1-\epsilon}\right)\left(\frac{\phi_k}{\omega}\frac{\epsilon}{1-\epsilon}\right)^{-\epsilon}}{\phi_k\left(1 + \frac{\epsilon}{1-\epsilon}\right)\left(\frac{\phi_k}{\omega}\frac{\epsilon}{1-\epsilon}\right)^{-\epsilon}} &= \frac{\nu_{11} + \nu_{21}}{\nu_{12} + \nu_{22}}\\
\frac{\phi_1^{1-\epsilon}}{\phi_2^{1-\epsilon}} &= \frac{\nu_{11} + \nu_{21}}{\nu_{12} + \nu_{22}}\\
\frac{\phi_1}{\phi_2} &= \left(\frac{\nu_{11} + \nu_{21}}{\nu_{12} + \nu_{22}}\right)^{\frac{1}{1-\epsilon}} && (6.83)
\end{aligned}$$

6.C Intertemporal Household Optimisation Problem

The inter temporal household optimisation problem reads

$$\max_{\vec{q},y} \int_0^T U(\vec{q_t}, y_t)\ \mathrm{e}^{t\,\rho t}\ \mathrm{d}t \tag{6.84}$$

with the utility function

$$U(Q(\vec{q_t}), y_t) = \begin{cases} y_t + \alpha \dfrac{\eta}{\eta - 1} Q(\vec{q_t})^{\frac{\eta-1}{\eta}} & \text{for } \eta \neq 1 \\ y_t + \alpha \ln Q(\vec{q_t}) & \text{for } \eta = 1 \end{cases} \tag{6.85}$$

and the sub utility of fish consumption

$$Q(\vec{q_t}) = \left(\sum_{i=1}^{\bar{i}} q_{it}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \tag{6.86}$$

.

The optimisation is subject to the per period household budget constraint (6.87), the stock change equation 6.2, the per period goods market clearing condition (6.88) and the condition of non-negativity of the number of firms (6.89). Furthermore it is assumed that the ecosystem is in a steady state.

$$\omega = y + \sum_{i=1}^{\bar{i}} p_i q_i \tag{6.87}$$

$$q_i = H_i = \sum_{k=1}^{\bar{k}} n_k h_{ik}(x_i) \tag{6.88}$$

$$n_k \geq 0 \tag{6.89}$$

The time index is omitted in the following.

As it is not known *ex ante* if condition (6.89) is binding the problem is split into cases depending on whether it is binding for each of the available tools. There are three cases to consider:

1. All tool types are in use

2. Only one tool type is in use

3. Not all tools are in use, but more than one is in use

In order to keep the analysis simple, for the remainder of this paper only two species and harvesting tools are considered (Assumption 5). This removes the third case from consideration.

6.C.1 Case 1

The current value hamiltonian in this case is:

$$\begin{aligned}
\mathcal{H}_c &= \omega - \sum_{i'=1}^{\bar{i}} p_{i'} q_{i'} + \alpha \frac{\eta}{\eta-1} \left(\sum_{i''=1}^{\bar{i}} q_{i''}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}} \\
&\quad + \sum_{i=1}^{\bar{i}} \mu_i \left(r_i (x_i - \underline{x}_i) \left(1 - \frac{\vec{\gamma}_i \vec{x}}{\kappa_i} \right) - q_i \right) \\
\Leftrightarrow \quad \mathcal{H}_c &= \omega + \alpha \frac{\eta}{\eta-1} \left(\sum_{i''=1}^{\bar{i}} q_{i''}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}} + \sum_{i=1}^{\bar{i}} \mu_i \left(r_i (x_i - \underline{x}_i) \left(1 - \frac{\vec{\gamma}_i \vec{x}}{\kappa_i} \right) - q_i \right) - p_i q_i
\end{aligned} \tag{6.90}$$

The corresponding optimality conditions are:

$$\frac{\partial \mathcal{H}_c}{\partial q_i} = -p_i(\vec{x}) + \alpha \left(\sum_{i'=1}^{\bar{i}} q_{i'}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\eta-\sigma}{\eta(\sigma-1)}} q_i^{-\frac{1}{\sigma}} - \mu_i = 0 \tag{6.91}$$

$$\dot{x}_i = r_i (x_i - \underline{x}_i) \left(1 - \frac{\vec{\gamma}_i \vec{x}_t}{\kappa_i} \right) - q_i \tag{6.92}$$

$$\dot{\mu}_i = {}^t\rho \mu_i - \frac{\partial \mathcal{H}_c}{\partial x_i} \tag{6.93}$$

$$x_{i\underline{t}} = x_{i1} \tag{6.94}$$

$$\mu_{i\bar{t}} = 0 \tag{6.95}$$

These conditions are used together with the assumption that $\bar{i} = \bar{k} = 2$ to determine optimal household consumption in a steady state.

Reranging (6.93):

$$
\begin{aligned}
& \dot{\mu}_i = {}^t\rho\mu_i - \frac{\partial \mathcal{H}_c}{\partial x_i} \\
\Leftrightarrow \quad & \dot{\mu}_i = {}^t\rho\mu_i - \sum_{i'=1}^{\bar{i}} \left[-\frac{\partial p_{i'}(\vec{x})}{\partial x_i} q_{i'} + \mu_{i'} \frac{\partial g_{i'}(\vec{x})}{\partial x_i} \right] \\
\Leftrightarrow \quad & \dot{\mu}_i = {}^t\rho\mu_i + \sum_{i'=1}^{\bar{i}} \left[\frac{\partial p_{i'}(\vec{x})}{\partial x_i} q_{i'} \right] - \sum_{i''=1}^{\bar{i}} \left[\mu_{i''} \frac{\partial g_{i''}(\vec{x})}{\partial x_i} \right] \\
\Leftrightarrow \quad & \dot{\mu}_i = {}^t\rho\mu_i + \sum_{i'=1}^{\bar{i}} \left[\frac{\partial p_{i'}(\vec{x})}{\partial x_i} q_{i'} \right] - \sum_{\substack{i''=1 \\ i''\neq i}}^{\bar{i}} \left[\mu_{i''} \frac{\partial g_{i''}(\vec{x})}{\partial x_i} \right] - \mu_i \frac{\partial g_i(\vec{x})}{\partial x_i} \\
\Leftrightarrow \quad & \dot{\mu}_i - \sum_{i'=1}^{\bar{i}} \left[\frac{\partial p_{i'}(\vec{x})}{\partial x_i} q_{i'} \right] = \mu_i \left({}^t\rho - \frac{\partial g_i(\vec{x})}{\partial x_i} \right) - \sum_{\substack{i''=1 \\ i''\neq i}}^{\bar{i}} \left[\mu_{i''} \frac{\partial g_{i''}(\vec{x})}{\partial x_i} \right]
\end{aligned}
$$

From the assumption of a steady state it follows that not only $\dot{\mu}_i = 0$ but also $\dot{x}_i = 0$. From the latter it follows that $q_i = g_i(\vec{x})$.

$$
\Leftrightarrow \quad - \sum_{i'=1}^{\bar{i}} \left[\frac{\partial p_{i'}(\vec{x})}{\partial x_i} q_{i'} \right] = \mu_i \left({}^t\rho - \frac{\partial g_i(\vec{x})}{\partial x_i} \right) - \sum_{\substack{i''=1 \\ i''\neq i}}^{\bar{i}} \left[\mu_{i''} \frac{\partial g_{i''}(\vec{x})}{\partial x_i} \right] \tag{6.96}
$$

There are $\bar{i}$ of equation (6.96). These constitute a linear system of equations which can be written as follows:

$$
{}^{\mu}b = {}^{\mu}A\vec{\mu} \tag{6.97}
$$

The components of the above are:

$$
{}^{\mu}A = \begin{pmatrix} {}^{\mu}a_{11} & \dots & {}^{\mu}a_{1\bar{j}} \\ \vdots & a_{ij} & \vdots \\ {}^{\mu}a_{\bar{i}1} & \dots & {}^{\mu}a_{\bar{i}\bar{j}} \end{pmatrix} \qquad a_{ii} = {}^t\rho - \frac{\partial g_i(\vec{x})}{\partial x_i} \qquad a_{ij} = -\frac{\partial g_j(\vec{x})}{\partial x_i}
$$

$$
\Leftrightarrow {}^{\mu}A = -(\mathrm{J}(g(\vec{x}))^{\intercal} + {}^t\rho\mathbf{I}^{\bar{i}}
$$

$$
{}^{\mu}\vec{b} = \begin{pmatrix} -\sum_{i'=1}^{\bar{i}} \left[\frac{\partial p_{i'}(\vec{x})}{\partial x_1} q_{i'} \right] \\ \vdots \\ -\sum_{i'=1}^{\bar{i}} \left[\frac{\partial p_{i'}(\vec{x})}{\partial x_{\bar{i}}} q_{i'} \right] \end{pmatrix}
$$

as $\frac{\partial p_{i'}(\vec{x})}{\partial x_{\bar{i}}} q_{i'} = 0$ if $i \neq i'$, ${}^{\mu}\vec{b}$ simplifies to

$$
{}^{\mu}\vec{b} = \begin{pmatrix} -\frac{\partial p_1(\vec{x})}{\partial x_1} q_1 \\ \vdots \\ -\frac{\partial p_{\bar{i}}(\vec{x})}{\partial x_{\bar{i}}} q_{\bar{i}} \end{pmatrix}
$$

Harvested quantities q_i are equal to stock growth $g_i(\vec{x})$ as steady state conditions are investigated.

$$
{}^{\mu}\vec{b} = \begin{pmatrix} -\frac{\partial p_1(\vec{x})}{\partial x_1} g_1(\vec{x}) \\ \vdots \\ -\frac{\partial p_{\bar{i}}(\vec{x})}{\partial x_{\bar{i}}} g_{\bar{i}}(\vec{x}) \end{pmatrix}
$$

Rearranging (6.91):

$$
\begin{aligned}
(6.91) \Leftrightarrow \quad & \alpha \left(\sum_{i'=1}^{\bar{i}} q_{i'}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\eta-\sigma}{\eta(\sigma-1)}} q_i^{-\frac{1}{\sigma}} = p_i(\vec{x}) + \mu_i \\
\Leftrightarrow \quad & \sum_{i'=1}^{\bar{i}} q_{i'}^{\frac{\sigma-1}{\sigma}} = \left(\frac{p_i(\vec{x}) + \mu_i}{\alpha q_i^{-\frac{1}{\sigma}}} \right)^{\frac{\eta(\sigma-1)}{\eta-\sigma}}
\end{aligned}
$$

The left hand side is identical in all $\bar{i}$ cases.

$$
\begin{aligned}
\Rightarrow \quad & \left(\frac{p_i(\vec{x}) + \mu_i}{\alpha q_i^{-\frac{1}{\sigma}}} \right)^{\frac{\eta(\sigma-1)}{\eta-\sigma}} = \left(\frac{p_{i'}(\vec{x}) + \mu_{i'}}{\alpha q_{i'}^{-\frac{1}{\sigma}}} \right)^{\frac{\eta(\sigma-1)}{\eta-\sigma}} \\
\Leftrightarrow \quad & \frac{p_i(\vec{x}) + \mu_i}{q_i^{-\frac{1}{\sigma}}} = \frac{p_{i'}(\vec{x}) + \mu_{i'}}{q_{i'}^{-\frac{1}{\sigma}}} \\
\Leftrightarrow \quad & q_{i'} = q_i \left(\frac{p_i(\vec{x} + \mu_i}{p_{i'}(\vec{x} + \mu_{i'}} \right)^{\sigma}
\end{aligned}
$$

plugging the above back into (6.91)

$$\begin{aligned}
\Rightarrow \quad p_i(\vec{x}) + \mu_i &= \alpha \left(\sum_{i'=1}^{\bar{i}} q_i \left(\frac{p_i(\vec{x} + \mu_i}{p_{i'}(\vec{x} + \mu_{i'}} \right)^{\sigma \frac{\sigma-1}{\sigma}} \right)^{\frac{\eta-\sigma}{\eta(\sigma-1)}} q_i^{-\frac{1}{\sigma}} \\
\Leftrightarrow \quad p_i(\vec{x}) + \mu_i &= \alpha q_i^{\frac{(\sigma-1)(\eta-\sigma)}{\sigma\eta(\sigma-1)} - \frac{1}{\sigma}} (p_i(\vec{x}) + \mu_i)^{\frac{\sigma(\sigma-1)(\eta-\sigma)}{\sigma\eta(\sigma-1)}} \left(\sum_{i'=1}^{\bar{i}} (p_{i'}(\vec{x}) + \mu_{i'})^{1-\sigma} \right)^{\frac{\eta-\sigma}{\eta(\sigma-1)}} \\
\Leftrightarrow \quad q_i^{-\frac{1}{\eta}} &= \alpha^{-1} (p_i(\vec{x}) + \mu_i)^{\frac{\sigma}{\eta}} \left(\sum_{i'=1}^{\bar{i}} (p_{i'}(\vec{x}) + \mu_{i'})^{1-\sigma} \right)^{\frac{\eta-\sigma}{\eta(\sigma-1)}} \\
\Leftrightarrow \quad q_i &= \alpha^{\eta} (p_i(\vec{x}) + \mu_i)^{-\sigma} \left(\sum_{i'=1}^{\bar{i}} (p_{i'}(\vec{x}) + \mu_{i'})^{1-\sigma} \right)^{\frac{\sigma-\eta}{1-\sigma}} \qquad (6.98)
\end{aligned}$$

The inter temporally optimised demand function (6.98) is analogous to the single period demand function with added shadow prices for stock depletion.

6.C.2 Case 2

For the second case the problem first needs to be converted into one with bundled goods according to the production technology.

The current Value Hamiltonian in this case is:

$$\begin{aligned}
\mathcal{H}_c =& \omega - n_k c_k + \alpha \frac{\eta}{\eta - 1} \left(\sum_{i=1}^{\bar{i}} (h_{ik}(\vec{x}) n_k)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1} \frac{\eta-1}{\eta}} \\
& + \sum_{i'=1}^{\bar{i}} \mu_{i'} \left(r_{i'}(x_{i'} - \underline{x}_{i'}) \left(1 - \frac{\vec{\gamma}_{i'} \vec{x}}{\kappa_{i'}} \right) - h_{i'k}(\vec{x}) n_k \right) \\
\Leftrightarrow \mathcal{H}_c =& \omega - n_k c_k - n_k \sum_{i''=1}^{\bar{i}} \mu_{i''} h_{i''k}(\vec{x}) + \alpha \frac{\eta}{\eta - 1} \left(\sum_{i=1}^{\bar{i}} (h_{ik}(\vec{x}) n_k)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1} \frac{\eta-1}{\eta}} \\
& + \sum_{i'=1}^{\bar{i}} \mu_{i'} r_{i'} (x_{i'} - \underline{x}_{i'}) \left(1 - \frac{\vec{\gamma}_{i'} \vec{x}}{\kappa_{i'}} \right) \qquad (6.99)
\end{aligned}$$

The corresponding optimality conditions are:

$$\frac{\partial \mathcal{H}_c}{\partial n_k} = 0 \tag{6.100}$$

$$\dot{x}_i = r_i(x_i - \underline{x}_i)\left(1 - \frac{\vec{\gamma}_i \vec{x}_t}{\kappa_i}\right) - n_k h_{ik}(\vec{x}) \tag{6.101}$$

$$\dot{\mu}_i = {}^t\rho\mu_i - \frac{\partial \mathcal{H}_c}{\partial x_i} \tag{6.102}$$

$$x_{i\underline{t}} = x_{i1} \tag{6.103}$$

$$\mu_{i\bar{t}} = 0 \tag{6.104}$$

For (6.102) the partial derivative of the Hamiltonian with respect to the stock levels is:

$$\frac{\partial \mathcal{H}_c}{x_i} = \alpha \left(\sum_{i=1}^{\bar{i}} (h_{ik}(\vec{x}) n_k)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} \sum_{i'=1}^{\bar{i}} \left[(h_{i'k}(\vec{x}) n_k)^{\frac{\sigma-1}{\sigma}-1} n_k \frac{\partial h_{i'k}(\vec{x}}{\partial x_i} \right]$$
$$+ \sum_{i''=1}^{\bar{i}} \left[\mu_{i''} \frac{\partial g_{i''}(\vec{x})}{\partial x_i} - n_k \mu_{i''} \frac{\partial h_{i''k}\vec{x}}{\partial x_i} \right]$$

using $h_{ik}(\vec{x}) = \chi_i \nu_{ik} e_k^*$ and $\frac{\partial h_{i'k}(\vec{x})}{\partial x_i} = \frac{\partial \chi_{i'}}{\partial x_i} \nu_{ik} e_k^*$ and rearanging a bit

$$\Leftrightarrow \quad \frac{\partial \mathcal{H}_c}{x_i} = \alpha \left(\sum_{i=1}^{\bar{i}} (\chi_i \nu_{ik} e_k^* n_k)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} \sum_{i'=1}^{\bar{i}} \left[(\chi_{i'} \nu_{i'k} e_k^* n_k)^{\frac{\sigma-1}{\sigma}-1} n_k \frac{\partial \chi_{i'}}{\partial x_i} \nu_{i'k} e_k^* \right]$$
$$+ \sum_{i''=1}^{\bar{i}} \left[\mu_{i''} \frac{\partial g_{''i}(\vec{x})}{\partial x_i} - n_k \mu_{i''} \frac{\partial \chi_{i''}}{\partial x_i} \nu_{i''k} e_k^* \right]$$

expand by χ_i

$$\begin{aligned}
\Leftrightarrow \quad \frac{\partial \mathcal{H}_c}{x_i} &= \alpha \left(\sum_{i=1}^{\bar{i}} \left(\chi_i \nu_{ik} e_k^* n_k\right)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} \sum_{i'=1}^{\bar{i}} \left[\left(\chi_{i'} \nu_{i'k} e_k^* n_k\right)^{\frac{\sigma-1}{\sigma}-1} n_k \frac{\partial \chi_{i'}}{\partial x_i} \nu_{i'k} e_k^* \chi_{i'} \chi_{i'}^{-1} \right] \\
&\quad + \sum_{i''=1}^{\bar{i}} \left[\mu_{i''} \frac{\partial g_{''i}(\vec{x})}{\partial x_i} - n_k \mu_{i''} \frac{\partial \chi_{i''}}{\partial x_i} \nu_{i''k} e_k^* \right] \\
\Leftrightarrow \quad \frac{\partial \mathcal{H}_c}{x_i} &= \alpha \left(\sum_{i=1}^{\bar{i}} \left(\chi_i \nu_{ik} e_k^* n_k\right)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} \sum_{i'=1}^{\bar{i}} \left[\left(\chi_{i'} \nu_{i'k} e_k^* n_k\right)^{\frac{\sigma-1}{\sigma}} \frac{\partial \chi_{i'}}{\partial x_i} \chi_{i'}^{-1} \right] \\
&\quad + \sum_{i''=1}^{\bar{i}} \left[\mu_{i''} \frac{\partial g_{''i}(\vec{x})}{\partial x_i} - n_k \mu_{i''} \frac{\partial \chi_{i''}}{\partial x_i} \nu_{i''k} e_k^* \right] \\
\Leftrightarrow \quad \frac{\partial \mathcal{H}_c}{x_i} &= \alpha \left(\sum_{i=1}^{\bar{i}} \left(h_{ik}(\vec{x}) n_k\right)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} \sum_{i'=1}^{\bar{i}} \left[\left(h_{i'k}(\vec{x}) n_k\right)^{\frac{\sigma-1}{\sigma}} \frac{\partial \chi_{i'}}{\partial x_i} \chi_{i'}^{-1} \right] \\
&\quad + \sum_{i''=1}^{\bar{i}} \left[\mu_{i''} \frac{\partial g_{''i}(\vec{x})}{\partial x_i} - n_k \mu_{i''} \frac{\partial \chi_{i''}}{\partial x_i} \nu_{i''k} e_k^* \right]
\end{aligned}$$

Now plug into (6.102)

$$\begin{aligned}
\Leftrightarrow \quad \dot{\mu}_i &= {}^t\rho \mu_i - \alpha \left(\sum_{i'''=1}^{\bar{i}} \left(h_{i'''k}(\vec{x}) n_k\right)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} \sum_{i'=1}^{\bar{i}} \left[\left(h_{i'k}(\vec{x}) n_k\right)^{\frac{\sigma-1}{\sigma}} \frac{\partial \chi_{i'}}{\partial x_i} \chi_{i'}^{-1} \right] \\
&\quad - \sum_{i''=1}^{\bar{i}} \left[\mu_{i''} \frac{\partial g_{''i}(\vec{x})}{\partial x_i} - n_k \mu_{i''} \frac{\partial \chi_{i''}}{\partial x_i} \nu_{i''k} e_k^* \right]
\end{aligned}$$

Using the steady state assumption

$$\begin{aligned}
\Leftrightarrow \quad 0 &= {}^t\rho \mu_i - \underbrace{\alpha \left(\sum_{i'''=1}^{\bar{i}} \left(g_{i'''}(\vec{x})\right)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} \sum_{i'=1}^{\bar{i}} \left[\left(g_{i'}(\vec{x})\right)^{\frac{\sigma-1}{\sigma}} \frac{\partial \chi_{i'}}{\partial x_i} \chi_{i'}^{-1} \right]}_{{}^\mu b_i(\vec{x})} \\
&\quad + \sum_{i''=1}^{\bar{i}} \left[\mu_{i''} \left(g_{i''}(\vec{x}) \frac{\partial \chi_{i''}}{\partial x_i} \chi_{i''}^{-1} - \frac{\partial g_{''i}(\vec{x})}{\partial x_i} \right) \right] \\
\Leftrightarrow \quad {}^\mu b_i(\vec{x}) &= {}^t\rho \mu_i + \sum_{i''=1}^{\bar{i}} \left[\mu_{i''} \left(g_{i''}(\vec{x}) \frac{\partial \chi_{i''}}{\partial x_i} \chi_{i''}^{-1} - \frac{\partial g_{i''}(\vec{x})}{\partial x_i} \right) \right] \\
\Leftrightarrow \quad {}^\mu b_i(\vec{x}) &= \mu_i \left({}^t\rho + g_i(\vec{x}) \frac{\partial \chi_i}{\partial x_i} \chi_i^{-1} - \frac{\partial g_i(\vec{x})}{\partial x_i} \right) + \sum_{\substack{i''=1 \\ i'' \neq i}}^{\bar{i}} \left[\mu_{i''} \left(g_{i''}(\vec{x}) \frac{\partial \chi_{i''}}{\partial x_i} \chi_{i''}^{-1} - \frac{\partial g_{i''}(\vec{x})}{\partial x_i} \right) \right]
\end{aligned} \tag{6.105}$$

There are $\bar{i}$ of these equations to solve as a linear system of equations they can be expressed simultaneously in the form

$$^{\mu}A\vec{\mu} = {}^{\mu}\vec{b} \tag{6.106}$$

with the solution

$$\vec{\mu} = {}^{\mu}A^{-1}\,{}^{\mu}\vec{b} \tag{6.107}$$

with ${}^{\mu}A(\vec{x}) \in \mathbb{R}^{\bar{i}\times\bar{i}}$, ${}^{\mu}\vec{b}(\vec{x}) \in \mathbb{R}^{\bar{i}}$ and $\vec{\mu} \in \mathbb{R}^{\bar{i}}$.

Let the elements of ${}^{\mu}A$ be given by ${}^{\mu}a_{ii'}$ and those of ${}^{\mu}\vec{b}$ by ${}^{\mu}b_i$.

$$\begin{aligned}
{}^{\mu}a_{ii} &= {}^{t}\rho + g_i(\vec{x})\frac{\partial\chi_i}{\partial x_i}\chi_i^{-1} - \frac{\partial g_i(\vec{x})}{\partial x_i} \\
{}^{\mu}a_{ii'} &= g_{i'}(\vec{x})\frac{\partial\chi_{i'}}{\partial x_i}\chi_{i'}^{-1} - \frac{\partial g_{i'}(\vec{x})}{\partial x_i} \qquad i \neq i' \\
{}^{\mu}b_i &= \alpha\left(\sum_{i''=1}^{\bar{i}}\left(g_{i''}(\vec{x})\right)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1}\sum_{i'''=1}^{\bar{i}}\left[\left(g_{i'''}(\vec{x})\right)^{\frac{\sigma-1}{\sigma}}\frac{\partial\chi_{i'''}}{\partial x_i}\chi_{i'''}^{-1}\right]
\end{aligned}$$

This can be simplified by using that $\frac{\partial\chi_i}{x_{i'}} = 0$ for $i \neq i'$.

$$\begin{aligned}
{}^{\mu}a_{ii} &= {}^{t}\rho + g_i(\vec{x})\frac{\partial\chi_i}{\partial x_i}\chi_i^{-1} - \frac{\partial g_i(\vec{x})}{\partial x_i} \\
{}^{\mu}a_{ii'} &= -\frac{\partial g_{i'}(\vec{x})}{\partial x_i} \qquad i \neq i' \\
{}^{\mu}b_i &= \alpha\left(\sum_{i''=1}^{\bar{i}}\left(g_{i''}(\vec{x})\right)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1}\left(g_i(\vec{x})\right)^{\frac{\sigma-1}{\sigma}}\frac{\partial\chi_i}{\partial x_i}\chi_i^{-1}
\end{aligned}$$

Rearranging (6.100) and using μ as derived above, the demand function in this case is the defined as follows:

$$
\begin{aligned}
\frac{\partial \mathcal{H}_c}{\partial n_k} &= -c_k + \alpha \left(\sum_{i=1}^{\bar{i}} \left(h_{ik}(\vec{x}) n_k\right)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} \\
& \sum_{i''=1}^{\bar{i}} h_{i''k}(\vec{x}) \left(h_{i''k}(\vec{x}) n_k\right)^{\frac{\sigma-1}{\sigma}-1} - \sum_{i'=1}^{\bar{i}} \mu_{i'} h_{i'k}(\vec{x}) \\
\Leftrightarrow \qquad 0 &= -c_k + \alpha n_k^{-\frac{1}{\eta}} \left(\sum_{i=1}^{\bar{i}} \left(h_{ik}(\vec{x}) n_k\right)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}} - \sum_{i''=1}^{\bar{i}} \mu_{i'} h_{i'k}(\vec{x}) \\
\Leftrightarrow \quad c_k + \sum_{i''=1}^{\bar{i}} \mu_{i'} h_{i'k}(\vec{x}) &= \alpha n_k^{-\frac{1}{\eta}} \left(\sum_{i=1}^{\bar{i}} \left(h_{ik}(\vec{x}) n_k\right)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}} \\
\Leftrightarrow \qquad n_k &= \alpha^{\eta} \left(c_k + \sum_{i''=1}^{\bar{i}} \mu_{i'} h_{i'k}(\vec{x}) \right)^{-\eta} \left(\sum_{i=1}^{\bar{i}} \left(h_{ik}(\vec{x}) n_k\right)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{(\eta-1)\sigma}{\sigma-1}} \qquad (6.108)
\end{aligned}
$$

6.C.3 Switching Between Cases

The condition for switching between the two cases above can be found using the optimality conditions of the second case and the Kuhn-Tucker conditions for non-negativity of Firms.

$$
\max \int_{t_1}^{\bar{t}} \omega - \sum_{k=1}^{\bar{k}} n_k c_k + \alpha \frac{\eta}{\eta - 1} \left(\sum_{i=1}^{\bar{i}} \left(\sum_{k'=1}^{\bar{k}} n_{k'} h_{ik'}(\vec{x}) \right)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}} \mathrm{e}^{-\,^{t}\rho t} \mathrm{d}t \qquad (6.109)
$$

subject to

$$
\dot{x}_i = g(\vec{x}) - \sum_{k=1}^{\bar{k}} n_k h_{ik}(\vec{x}) \qquad (6.110)
$$

$$
-n_k \leq 0 \qquad (6.111)
$$

The Hamiltonian for this problem is given by:

$$\mathcal{H}_c = \omega - \sum_{k=1}^{\bar{k}} n_k c_k + \alpha \frac{\eta}{\eta - 1} \left(\sum_{i=1}^{\bar{i}} \left(\sum_{k'=1}^{\bar{k}} n_{k'} h_{ik'}(x_i) \right)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}}$$
$$+ \sum_{k'''=1}^{\bar{k}} \lambda_{k'''} n_{k'''} + \sum_{i'=1}^{\bar{i}} \mu_{i'} \left(g_{i'}(\vec{x}) - \sum_{k''=1}^{\bar{k}} n_{k''} h_{i'k''}(x_{i'}) \right) \tag{6.112}$$

The corresponding first order conditions are then:

$$\frac{\partial \mathcal{H}_c}{\partial n_k} = 0 \tag{6.113}$$

$$\dot{x}_i = g(\vec{x}) - \sum_{k=1}^{\bar{k}} n_k h_{ik}(x_i) \tag{6.114}$$

$$\dot{\mu}_i = {}^t\rho \mu_i - \sum_{k=1}^{\bar{k}} n_k h_{ik}(x_i) \tag{6.115}$$

The transversality conditions are:

$$x_{it} = x_{i0} \tag{6.116}$$

$$\mu_{i\bar{t}} = 0 \tag{6.117}$$

The Kuhn-Tucker conditions are:

$$\lambda_k \geq 0 \tag{6.118}$$

$$-n_k \leq 0 \tag{6.119}$$

$$-\lambda_k n_k = 0 \tag{6.120}$$

The condition for switching between cases is found by using condition (6.120) in conjunction with (6.100) under assumption that $\bar{i} = \bar{k} = 2$ for case 2 that is one firm being active, as the sole active firm, and the other is not.

Let $n_1 = 0$, $n_2 > 0$, and hence $\lambda_1 \geq 0$ and $\lambda_2 = 0$.

Starting from (6.100) for Tool 1:

$$
\begin{aligned}
0 = -c_1 + \alpha &\left(\sum_{i=1}^{\bar{i}} \left(\sum_{k'=1}^{\bar{k}} n_{k'} h_{ik'}(x_i) \right)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} \\
&\sum_{i''=1}^{\bar{i}} \left[h_{i''1}(x_{i''}) \left(\sum_{k''=1}^{\bar{k}} n_{k''} h_{i''k''}(x_{i''}) \right)^{\frac{\sigma-1}{\sigma}-1} \right] \\
&+ \lambda_1 - \sum_{i'=1}^{\bar{i}} \left[\mu_{i'} h_{i'1}(x_{i'}) \right]
\end{aligned}
$$

Substituting the n_k as specified above.

$$
\begin{aligned}
\Rightarrow \quad 0 = -c_1 + \alpha &\left(\sum_{i=1}^{\bar{i}} \left(n_2 h_{i2}(x_i) \right)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} \sum_{i''=1}^{\bar{i}} \left[h_{i''1}(x_{i''}) \left(n_2 h_{i''2}(x_{i''}) \right)^{\frac{\sigma-1}{\sigma}-1} \right] \\
&+ \lambda_1 - \sum_{i'=1}^{\bar{i}} \left[\mu_{i'} h_{i'1}(x_{i'}) \right]
\end{aligned}
$$

Using $\lambda_1 \geq 0$.

$$
\Leftrightarrow \quad 0 \geq n_2^{-\frac{1}{\eta}} \alpha \left(\sum_{i=1}^{\bar{i}} h_{i2}(x_i)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1} \sum_{i''=1}^{\bar{i}} \left[h_{i''1}(x_{i''}) h_{i''2}(x_{i''})^{\frac{\sigma-1}{\sigma}-1} \right] - c_1 - \sum_{i'=1}^{\bar{i}} \left[\mu_{i'} h_{i'1}(x_{i'}) \right]
$$

Substitute n_2 by (6.108). This is possible due to the assumption of Tool 2 being the only tool in use.

$$\Rightarrow \quad 0 \geq \overbrace{\left(c_2 + \sum_{i'''=1}^{\bar{i}} \mu_{i'''} h_{i'''2}(x_{i'''})\right) \alpha^{-1} \left(\sum_{i^{iv}=1}^{\bar{i}} h_{i^{iv}2}(x_{i^{iv}})^{\frac{\sigma-1}{\sigma}}\right)^{-\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}}}^{n_2^{-\frac{1}{\eta}}}$$
$$\alpha \left(\sum_{i=1}^{\bar{i}} h_{i2}(x_i)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}\frac{\eta-1}{\eta}-1}$$
$$\sum_{i''=1}^{\bar{i}} \left[h_{i''1}(x_{i''}) h_{i''2}(x_{i''})^{\frac{\sigma-1}{\sigma}-1}\right] - c_1 - \sum_{i'=1}^{\bar{i}} \left[\mu_{i'} h_{i'1}(x_{i'})\right]$$
$$\Leftrightarrow \quad 0 \geq \left(c_2 + \sum_{i'''=1}^{\bar{i}} \mu_{i'''} h_{i'''2}(x_{i'''})\right) \left(\sum_{i=1}^{\bar{i}} h_{i2}(x_i)^{\frac{\sigma-1}{\sigma}}\right)^{-1} \sum_{i''=1}^{\bar{i}} \left[h_{i''1}(x_{i''}) h_{i''2}(x_{i''})^{\frac{\sigma-1}{\sigma}-1}\right]$$
$$- c_1 - \sum_{i'=1}^{\bar{i}} \left[\mu_{i'} h_{i'1}(x_{i'})\right]$$

Substitute minimum harvesting costs (6.20) and equilibrium harvests (6.6) with (6.9) for c_k and $h_{ik}(x_i)$.

$$\Rightarrow \quad 0 \geq \left(\phi_2 + \omega e_2^* + \sum_{i'''=1}^{\bar{i}} \left[\mu_{i'''} \chi_{i'''} \nu_{i'''2} e_2^{*\epsilon}\right]\right) \left(\sum_{i=1}^{\bar{i}} \left(\chi_i \nu_{i2} e_2^{*\epsilon}\right)^{\frac{\sigma-1}{\sigma}}\right)^{-1}$$
$$\sum_{i''=1}^{\bar{i}} \left[\chi_{i''} \nu_{i''1} e_1^{*\epsilon} \left(\chi_{i''} \nu_{i''2} e_2^{*\epsilon}\right)^{\frac{\sigma-1}{\sigma}-1}\right] - \phi_1 - \omega e_1^* - \sum_{i'=1}^{\bar{i}} \left[\mu_{i'} \chi_{i'} \nu_{i'1} e_1^{*\epsilon}\right]$$
$$\Leftrightarrow \quad 0 \geq e_1^{*\epsilon} e_2^{*-\epsilon} \left(\phi_2 + \omega e_2^* + e_2^{*\epsilon} \sum_{i'''=1}^{\bar{i}} \left[\mu_{i'''} \chi_{i'''} \nu_{i'''2}\right]\right) \left(\sum_{i=1}^{\bar{i}} \left(\chi_i \nu_{i2}\right)^{\frac{\sigma-1}{\sigma}}\right)^{-1}$$
$$\sum_{i''=1}^{\bar{i}} \left[\chi_{i''} \nu_{i''1} \left(\chi_{i''} \nu_{i''2}\right)^{\frac{\sigma-1}{\sigma}-1}\right] - \phi_1 - \omega e_1^* - e_1^{*\epsilon} \sum_{i'=1}^{\bar{i}} \left[\mu_{i'} \chi_{i'} \nu_{i'1}\right]$$
$$\Leftrightarrow \quad 0 \geq \left(\sum_{i=1}^{\bar{i}} \left(\chi_i \nu_{i2}\right)^{\frac{\sigma-1}{\sigma}}\right)^{-1}$$
$$\sum_{i''=1}^{\bar{i}} \left[\chi_{i''} \nu_{i''1} \left(\chi_{i''} \nu_{i''2}\right)^{\frac{\sigma-1}{\sigma}-1}\right] - \frac{e_1^{*-\epsilon} \left(\phi_1 + \omega e_1^* + e_1^{*\epsilon} \sum_{i'=1}^{\bar{i}} \left[\mu_{i'} \chi_{i'} \nu_{i'1}\right]\right)}{e_2^{*-\epsilon} \left(\phi_2 + \omega e_2^* + e_2^{*\epsilon} \sum_{i'''=1}^{\bar{i}} \left[\mu_{i'''} \chi_{i'''} \nu_{i'''2}\right]\right)}$$

Substitute (6.9) for e_k^* and rearrange.

$$\Rightarrow \quad 0 \geq \left(\sum_{i=1}^{\bar{i}} (\chi_i \nu_{i2})^{\frac{\sigma-1}{\sigma}} \right)^{-1} \sum_{i''=1}^{\bar{i}} \left[\chi_{i''} \nu_{i''1} (\chi_{i''} \nu_{i''2})^{\frac{\sigma-1}{\sigma}-1} \right] - \frac{\frac{\phi_1^{1-\epsilon}}{\omega^{-\epsilon}} \frac{\epsilon^{-\epsilon}}{(1-\epsilon)^{1-\epsilon}} \sum_{i'=1}^{\bar{i}} \left[\mu_{i'} \chi_{i'} \nu_{i'1} \right]}{\frac{\phi_2^{1-\epsilon}}{\omega^{-\epsilon}} \frac{\epsilon^{-\epsilon}}{(1-\epsilon)^{1-\epsilon}} \sum_{i'''=1}^{\bar{i}} \left[\mu_{i'''} \chi_{i'''} \nu_{i'''2} \right]}$$

$$\Leftrightarrow \quad 0 \geq \left(\sum_{i=1}^{\bar{i}} (\chi_i \nu_{i2})^{\frac{\sigma-1}{\sigma}} \right)^{-1} \sum_{i''=1}^{\bar{i}} \left[\chi_{i''} \nu_{i''1} (\chi_{i''} \nu_{i''2})^{\frac{\sigma-1}{\sigma}-1} \right] - \frac{\phi_1^{1-\epsilon} \sum_{i'=1}^{\bar{i}} \left[\mu_{i'} \chi_{i'} \nu_{i'1} \right]}{\phi_2^{1-\epsilon} \sum_{i'''=1}^{\bar{i}} \left[\mu_{i'''} \chi_{i'''} \nu_{i'''2} \right]} \tag{6.121}$$

6.C.4 Conditions For No Effect of Bycatch under Optimal Harvesting

Without loss of generality the derivation is performed for the shadow price of species 1 to changes in the catch composition of harvesting gear type 2. Shadow prices of a single species, when ecosystem interaction is not present is given by (6.28).

$$\mu_i = \left({}^t\rho - \frac{\partial g_i(\vec{x})}{\partial x_i} \right)^{-1} \left(-\frac{\partial p_i(x_i)}{\partial x_i} g_i(\vec{x}) \right) \tag{6.28}$$

The derivation of the shadow price to the individual harvesting efficiency $\nu_i' k$ is then given by the following equation.

$$\frac{\mathrm{d}\mu_i}{\mathrm{d}\nu_{i'k}} = \left({}^t\rho - \frac{\partial g_i(\vec{x})}{\partial x_i} \right)^{-1} \left(-\frac{\partial \frac{\partial p_i(x_i)}{\partial x_i}}{\partial \nu_{i'k}} g_i(\vec{x}) \right)$$

This is plugged in to the equality between different derivatives of shadow prices to changing harvesting efficiencies.

$$\frac{\mathrm{d}\mu_1}{\mathrm{d}\nu_{12}} = \frac{\mathrm{d}\mu_1}{\mathrm{d}\nu_{22}}$$

$$\left({}^t\rho - \frac{\partial g_1(\vec{x})}{\partial x_1} \right)^{-1} \left(-\frac{\partial \frac{\partial p_1(x_1)}{\partial x_1}}{\partial \nu_{12}} g_1(\vec{x}) \right) = \left({}^t\rho - \frac{\partial g_1(\vec{x})}{\partial x_1} \right)^{-1} \left(-\frac{\partial \frac{\partial p_1(x_1)}{\partial x_1}}{\partial \nu_{22}} g_1(\vec{x}) \right)$$

$$\frac{\partial \frac{\partial p_1(x_1)}{\partial x_1}}{\partial \nu_{12}} = \frac{\partial \frac{\partial p_1(x_1)}{\partial x_1}}{\partial \nu_{22}}$$

The price derivative to stock change is given by the following equation.

$$\frac{\partial p_1(x_1)}{\partial x_1} = -\chi_1^{-2}(\nu_{11}\nu_{22} - \nu_{12}\nu_{21})^{-1}(\nu_{22}\,{}^pb_1 - \nu_{21}\,{}^pb_2) \tag{6.122}$$

Plugging this into the expression above then yields the same condition for no effect of bycatch as in the open-access case.

$$\begin{aligned}
\frac{\partial\frac{\partial p_1(x_1)}{\partial x_1}}{\partial \nu_{12}} &= \frac{\partial\frac{\partial p_1(x_1)}{\partial x_1}}{\partial \nu_{22}} && (6.123)\\
\frac{\nu_{21}\left({}^pb_1\nu_{22} - {}^pb_2\nu_{21}\right)}{\left(\nu_{12}\nu_{21} - \nu_{11}\nu_{21}\right)^2\left(-\chi_1^2\right)} &= \frac{\nu_{21}\left({}^pb_2\nu_{11} - {}^pb_1\nu_{12}\right)}{\left(\nu_{12}\nu_{21} - \nu_{11}\nu_{22}\right)^2\left(-\chi_1^2\right)}\\
{}^pb_1\nu_{22} - {}^pb_2\nu_{21} &= {}^pb_2\nu_{11} - {}^pb_1\nu_{12}\\
{}^pb_1(\nu_{22} + \nu_{12}) &= {}^pb_2(\nu_{11} + \nu_{21})\\
\frac{{}^pb_1}{{}^pb_2} &= \frac{\nu_{11} + \nu_{21}}{\nu_{12} + \nu_{22}} && (6.124)
\end{aligned}$$

substitute ${}^pb$ with (6.59)

$$\begin{aligned}
\frac{\phi_1\left(1 + \frac{\epsilon}{1-\epsilon}\right)\left(\frac{\phi_k}{\omega}\frac{\epsilon}{1-\epsilon}\right)^{-\epsilon}}{\phi_k\left(1 + \frac{\epsilon}{1-\epsilon}\right)\left(\frac{\phi_k}{\omega}\frac{\epsilon}{1-\epsilon}\right)^{-\epsilon}} &= \frac{\nu_{11} + \nu_{21}}{\nu_{12} + \nu_{22}}\\
\frac{\phi_1^{1-\epsilon}}{\phi_2^{1-\epsilon}} &= \frac{\nu_{11} + \nu_{21}}{\nu_{12} + \nu_{22}}\\
\frac{\phi_1}{\phi_2} &= \left(\frac{\nu_{11} + \nu_{21}}{\nu_{12} + \nu_{22}}\right)^{\frac{1}{1-\epsilon}} && (6.125)
\end{aligned}$$

6.D Potential Mortality under TAC with Discarding

The derivation of potential mortality under TAC goes as follows. For the derivation it is assumed that q_1 is bound by the TAC and q_2 is harvested unrestricted through discarding. Both species are harvested using the same gear k and effort level e_k

$$q_1 = \nu_{1k}\chi_1 n_k e_k^{\epsilon} \tag{6.126}$$

$$q_2 = \nu_{2k}\chi_2 n_k e_k^{\epsilon} \tag{6.127}$$

rearanging to isolate the identical fleet size and harvesting effort determingn quantities and setting both to be equal

$$q_1 \nu_{1k}^{-1} \chi_1^{-1} = q_2 \nu_{2k}^{-1} \chi_2^{-1} \tag{6.128}$$

$$q_2 = q_1 \frac{\nu_{2k} \chi_2}{\nu_{1k} \chi_1} \tag{6.129}$$

Chapter 7

Conclusion

Management of an ocean is a highly complex matter. In this thesis I focus only on the fisheries and related economic activities of the marine ecosystem contained in the ocean, yet, even considering only this aspect, management is far from simple. Here I discuss the lessons learned, how they can be applied to improve management of marine ecosystems in general and in the German Bight in particular. I further consider possible extensions and limitations of the presented research.

Returning to the research questions presented in the introduction:

- Which interactions are present between managed species in a multi-species fishery and what are the consequences of these interactions for management?
- What are the vulnerabilities of a fishing industry to changes in social and ecological drivers especially in the context of an interconnected socio-ecological system?
- What thresholds are present in the socio-ecological system and what are their consequences for management?

I find that the answers to these questions are highly intertwined. While each of the chapters had a main thrust with respect to one or another of the questions, they nonetheless all provide some insight to all of them. Below I summarize the findings with respect to each of the questions.

The Importance of Interaction Effects

Fisheries, the ecosystems impacted by fisheries, the households consuming fish products, and the local fishing culture make up a highly interconnected socio-ecological system (SES) (Chapter 2). I show that it is generally necessary to include interactions between species within the ecosystem, in harvesting and in consumer demand when setting quotas, if overfishing is to be avoided (Chapter 4). This finding is derived from the change in open-access dynamics when these interactions are present compared to the hypothetical case where each species develops independently. If management measures are designed based on single species assessment the interaction effects will cause cross-species impacts that may lead to overharvesting of other species present. This has the potential to cross a tipping point that the decision maker was not aware of. The application of quantity based management measures (e.g. quotas) alleviates this issue only partly. In the case of perfect compliance, and each species having been allocated a quota that ensures sustainable stock developments, quantity based management will insulate the stocks from interaction effects in harvesting and consumer demand. However, as I discuss in Chapter 6, these interaction effects determine the incentive to deviate from the quota. If quotas are set purely on ecological basis, there may exist a large incentive to violate the quota. This can be mitigated by taking the harvesting and market effects into account, thereby avoiding the phenomenon of choke species. This occurs, when a fisher is forced to stop operating, as the quota of one of the simultaneously harvested species has been reached, even though unused quota for another species remains. Regulating the allowable catch in an incentive compatible way would require that all quotas are exhausted as simultaneously as possible. If the more restrictive quota cannot be increased, due to ecological sustainability concerns, the previously less restrictive quota would have to be set at a lower level.

While prescribing incentive compatible quotas appears to be a satisfying solution, the incentive of the fishers to violate the quota of the choke species is also their incentive to innovate novel fishing techniques that allow for more selectivity in harvesting. Hence, the proposed practice of setting incentive compatible quotas would also remove the incentive for fishers to develop more selective fishing gear. Fishers in the North Sea have a long history of adapting their fishing practices to changing ecological an regulatory environments (Chapter 3). Removing their incentive to continue to do so would be doing them a disservice and would preclude increased harvests of the more abundant species, while maintaining the low harvests of the more vulnerable species, through more selective gear.

In this thesis I presented a model that included three types of interaction effects that could affect the dynamics of multiple fish species (interactions between species within the ecosystem, in harvesting, and in consumer demand). The choice, which interaction effects to include in the model were based on a review of existing literature as well as discussions with researchers at the Thünen-Institute of Sea Fisheries. A limit to the aim of including all interaction effects affecting the decision making of all involved actors, is that the scope of included interactions will inevitably grow, due to the connected nature of both ecosystems and human society. Consequently the question for future research is to determine which of the extended interactions are relevant to the object of research.

Vulnerabilities of a Fishing Fleet

In order to assess the vulnerability of the fisheries in the North Sea and the German Bight, it was first necessary to clarify what is meant by the term vulnerability and by its components sensitivity and adaptive capacity. In Chapter 2 I present a systematic review of the existing use of the terms in literature related to marine context. A result of this work was the derivation of guiding principles for the operationalisation of SES frameworks based on three steps: The phrasing of the issue to be investigated, the identification of the components of the SES impacted and their connections followed by the analysis. A further result of this was the realisation that in previous vulnerability assessments socio-cultural aspects of the socio-ecological system (SES) are often under-represented in marine contexts. As described above, omitting such interactions can drastically alter the dynamics of the system and, hence, the vulnerability of individual actors within the system and the system as a whole. This is especially important, when the system in question is exposed to changing environmental and regulatory drivers, as the North Sea has. As a consequence of the changing environment and fishery regulations, the fisheries in the North Sea adapted, changing harvesting gear and target species over time. However, this adaptive capacity has limits. When these are crossed the profitability and existence of the fisheries and associated economic and cultural value may be lost (Chapter 3).

In Chapter 5 the vulnerability of the fishing fleets included in the bio-economic models is investigated. In this Chapter the focus lies on the economic viability of the fishing fleet measured by marginal changes in profit. This analysis is based on a framework for the assessment and quantification of sensitivity, adaptive capacity, and vulnerability presented in the same chapter. The application of this framework to the bio-economic model (Chapter 4) demonstrates that an actor can be vulnerable to drivers that are not directly impacting them but act through the connections in the SES, and that when these connections are properly modelled these indirect effects can also be quantified, reinforcing the importance of accounting for interaction effects. The analytical work in Chapter 5 reinforces the more qualitative results in Chapter 3. While fishers can generally adapt their behaviour to changes in drivers, this is not true in all cases. For certain drivers and/or exposure levels the impact is not mitigated by the fishers' effort choice, the adaptation variable used in the model based analysis. However, the choice of the adaptation variable is a limiting factor in our analytical results, due to the limitations of the model. In the model, harvests depend on the effort, a generalised term encompassing all behaviour choices of the fisher. Similarly variable costs are proportionate to the effort level. In reality it may matter if adaptation occurs through travelling to different fishing grounds, changing gear in a more subtle way than what is presented here, or increasing fishing hours.

The Importance of Threshold Effects

Throughout this thesis the importance of threshold effects, caused by the crossing of a tipping point in a driver, has been emphasized. While these phenomena are widely regarded as important there is some variation in definitions found in literature and terminology used to describe them (see Table 2.1). In Chapter 2 it is discussed that the tipping point is often described as part of the ecosystem component of the SES, but may also be located within the coupled socio-economic system. In the analysis of the bio-economic model presented in Chapter 4 I find that due to the interconnectedness of the system, a tipping point in the ecosystem can be triggered not only by ecological drivers but also by economic drivers. Consequently, the knowledge which specific system contains the tipping point is not as important as the knowledge that the overall SES contains a tipping point.

For the SES of the North Sea multiple tipping points are identified in both the ecosystem as well as the connected socio-economic system. For the ecosystem Sguotti et al. (2022) demonstrate that the species composition in the North Sea has undergone a regime shift, due to crossing tipping points in environmental and harvesting pressures. For the socio-economic system 3 highlights that small scale German fishery may also be on the verge of collapse, due to environmental, price, and regulatory pressures. This tipping point in the economic viability of the fisheries would have consequences for the regional economies of the ports the vessels operate out of.

The possibility of a regime shift in stock abundance is reflected in the bio-economic model of Chapters 4, 5, and 6. The derived optimal harvest rates depend on the minimum viable population, the parameter responsible for the tipping behaviour in the ecosystem. An increase in the minimum viable population, reduces the stability of the system by shrinking the domain of attraction of the interior steady state, and decreases the optimal harvest amount.

Extensions and Limitations

The bio-economic model introduced in Chapter 4 and used in Chapters 5 and 6 has limitations that arise from the choices that have to be made when building a model: Where to draw the boundaries of the system and what degree of complexity is necessary to answer the research questions.

In order to enable analytical derivation of results the model, the boundaries of the system are drawn in such a way that only those actors and systems are included, which are necessary to answer the research questions: The resource (fish stocks), the harvesting actors (fishery firms), and the consumers (households). This excludes non-use benefits of the resource and non-market interactions between actors.

Furthermore, in order for the model to be tractable several assumptions about the functioning of the market are made. These are common in the bio-economic literature, but clash with real world observations. Most striking are the assumptions of free entry and exit from the market for fishing firms and of fishery using effort as the sole input in production. While in reality, as described in Chapter 3, the fishers are constrained in acquiring the necessary capital and have experienced an ageing of the fleet requiring investments into upkeep. This limits the ability of a prospective fisher to enter the market, as there is a significant amount of upfront capital necessary to buy a vessel and gear in order to start fishing. When the capital has been acquired in the form of a loan, this limits the ability to exit the market as loan repayment has to be maintained. Modelling fisheries as reliant on effort as the sole input further omits the ageing of vessels, requiring investment into upkeep. As a consequence of this the model does not include the possibility of the economic tipping point described in Chapter 3. These issues could be addressed by extending the model to include capital stocks for the fishing firms, with a minimum capital stock needed to begin operation.

This issue does not affect the steady state analysis, however, as here the fixed costs of operation fill the role of investment into upkeep needed in steady state and there is no entry or exit from the market. In dynamic runs of the model, this issue will cause fleet adjustment to be overly flexible, responding too quickly to small changes in stock abundance. However, the policy relevance of a predicted change in fleet size is still given, as it indicates a pressure on fishers to enter or exit the market, even if the change in fleet size will happen much slower in reality.

A further limitation stems from the focus of this thesis on the implications of structural uncertainty. In the modelling context this was the investigation which of the interaction effects are relevant for the dynamics of the system and relevant for management. As a consequence of this choice random shocks and uncertainty in parameters are not included in the model. However, the North Sea is a system subject to time varying pressures due to human impacts and climate change in addition to large random shocks due to weather events or recruitment success. The impacts of these drivers and shocks are observable in the time series presented in Chapter 3. The model presented in this thesis does not include these stochastic properties in the differential equations describing stock change. In so far as the random shocks can be assumed to be symmetrically distributed with a zero mean, the steady state results derived can be interpreted as the expected long term state of the system, if drivers remain constant. Extending the model to include stochastic growth allows deriving probabilistic statements about the future state of the system. Including time varying drivers allows for the evaluation of the effects of e.g. climate change where the productivity of the ecosystem is impacted increasingly over time.

Concluding Remarks

In conclusion I find that the Socio-Ecological System centred around the North Sea fisheries is highly interconnected and dynamic, requiring a management approach that incorporates these properties. If the economic drivers of fishing effort and incentives for non-compliance are ignored, management is either ineffective, due to non-compliance, or unnecessarily expensive, due to high enforcement costs. The costs of enforcement range beyond the pure monetary costs of employing additional personnel to police the fishermen, the installation of technical measures such as the satellite based vessel monitoring system, or cameras to monitor fishers behaviour on the decks of their own vessels. There is also a social cost of enforcement. As surveillance increases the quality of life of fishers decreases. These costs, both monetary and social, provide ample reason to include economic and social drivers of fishing effort in the management of fisheries, in addition to the state and dynamics of the resource and the ecosystem it resides in.

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Appendix A

Abstract

A.1 English Abstract

The fishery in the German Bight and the greater North Sea are part of a highly interconnected socio-ecological system (SES). This SES consists of an ecosystem consisting of multiple species which are harvested by a number of different fishing métiers and sold to consumers. In this thesis I investigate the importance of the various interconnections between the dynamics of different species and human activities, the implications for the vulnerability of the fisheries. Managing the fisheries at the heart of this SES is made more complicated by the existence of tipping points in the economic viability of the fisheries and within the ecosystem, which can be triggered by a wide variety of drivers.

In Chapter 2 the results of a targeted literature review on empirical assessments of SES and tipping points in the marine realm and their use in ecosystem-based management are presented. The literature contains a wide variety of terminologies and definitions of these concepts, making it difficult to discern guiding principles for the practical application. Furthermore, existing work in empirical assessment of SES vulnerabilities (to tipping points or otherwise) tends to over-simplify the behaviour of human actors. This is the case, even while human actors tend to be one of the largest pressures on marine ecosystems with their behaviour significantly impacting stock dynamics and ecosystem composition.

Chapter 3 gives an overview of the history of the coastal fishery targeting mainly plaice and sole in the North Sea and the challenges faced due to climate change. Climate change causes changes in the spatial distribution of fish stocks due to a changing temperature gradient in the North Sea as well as changes in the productivity of the stocks. This in turn has consequences for the ecosystem and socio-ecological system the stocks are a part of. This chapter describes the challenges these changes pose for the fishery in relation to the fishery's adaptive capacity. As the fisheries are at the bottom with regards to the order of decision making on European fisheries their leeway to adapt to these changes is

severely limited. Consequently, changes in management practices may be necessary if this fishery is to be maintained.

Chapter 4 presents a model that includes interaction between species dynamics within the ecosystem, through simultaneous harvests, and through consumer substitution preferences. The main results, besides replicating the finding that bycatch can increase harvesting mortality, are that simultaneous harvest properties may have no effects on stocks, and that the harvesting economy may change dramatically if discards are banned. Understanding the interrelation of simultaneous harvests and market forces is essential in designing overarching policy where economic effects, such as changing employment, need to be considered while also ensuring sustainable use of the ecosystem.

In Chapter 5 a novel framework to assess sensitivity, adaptive capacity, and vulnerability of an actor to a driver is developed based on derivatives of equations describing their behaviour. The framework is then applied to the bio-economic model developed in Chapter 4. The results indicate that fishers' profits are most vulnerable to changes in plaice prices, returns to effort, stock harvesting efficiency of plaice, plaice stocks, and wages. These results provide additional context for decision makers setting harvest policies, especially if the existence of the fishery and not only the protection of the stock is the management goal.

Finally the optimal harvest quantities are derived based on maximizing the intertemporal welfare of the representative household in Chapter 6. I find that the interaction effects play an important role in specifying optimal harvests. Furthermore, their importance in the design of total allowable catch and quantity tax based management is investigated. While it may superficially seem that quota based management would cancel out all interactions besides those within the ecosystem, the incentive of fishers to violate the quota or a discard ban will depend on the specifics of the simultaneous catch properties and substitution behaviour in consumer demand. Consequently, this incentive can be minimized by taking these properties into account while designing the management policy.

A.2 German Abstract

Die Fischerei in der deutschen Bucht und in der weiteren Nordsee sind teil eines eng vermaschten sozio-ökologischen Systems (SES). Dieses SES besteht aus dem Ökosystem aus verschiedenen Spezies, welche von Fischern verschiedener Métiers gefangen und an Konsumenten verkauft werden. In dieser Dissertation untersuche ich die Auswirkungen der Kopplungen zwischen den Dynamiken der der verschiedenen Spezies und menschlichen Aktivitäten und deren Auswirkungen auf die Vulnerabilität der Fischerei. Management der Fischerei im Kern des SES wird erschwert durch die Existenz von Kipppunkten in der Rentabilität der Fischerei sowie innerhalb des Ökosystem, welche durch verschiedene Treiber ausgelöst werden können.

In Kapitel 2 werden die Ergebnisse einer gezielten Literaturrecherche über die empirische Bewertung von SES und Kipppunkten im marinen Kontext für Ökosystem basiertes Management präsentiert. Die Literatur beinhaltet eine große Anzahl verschiedener Terminologien und Definitionen dieser Konzepte. Dies erschwert es Leitlinien für die praktische Anwendung ab zu leiten. Des Weiteren wird hervorgehoben, dass bestehenden empirische Untersuchungen menschliche Akteure oft nur stark vereinfacht berücksichtigt werden. Dies ist der Fall, obwohl menschliche Akteure oft die größten Stressoren in marinen Ökosystemen bilden. Ihr Verhalten kann Ökosystemdynamiken stark beeinflussen.

3 gibt eine Übersicht über die Geschichte der küstennahen Fischerei, welche hauptsächlich Scholle und Seezunge als Zielart hat, und die Herausforderungen die im Zuge des Klimawandels auf sie zukommen. Der Klimawandel bewirkt eine räumliche Veränderung der Fischbestände in Folge des sich verändernden Temperaturgradienten in der Nordsee sowie eine Veränderung der Produktivität der Bestände. Hieraus folgen Konsequenzen für das SES in dem sich diese Bestände befinden. In diesem Kapitel werden die Schwierigkeiten die aus diesen Veränderungen für die Fischer resultieren untersucht. Da sich die Fischer in der Entscheidungshierarchie bezüglich der Fangmengen in der Nordsee an unterster Stelle befinden ist ihre Fähigkeit auf die Herausforderungen zu reagieren stark eingeschränkt. Soll die Fischerei aufrecht erhalten werden, sind gegebenenfalls Änderungen in Managementpraktiken notwendig.

In Kapitel 4 wird ein Modell präsentiert, in dem Interaktionen zwischen Speziesbestandsdynamiken innerhalb des Ökosystems, durch simultanen Fang und durch die Substitutionspräferenzen der Konsumenten beinhaltet sind. Anhand des Modells wird

gezeigt, dass unter bestimmten Bedingungen auch starke Interaktionen im Fang gegebenenfalls keine Auswirkung auf die Bestandsdynamiken und ökonomischen variablen haben. Des Weiteren wird aufgezeigt, wie ein Verbot von Rückwurf die Fangdynamiken stark verändert. Das Verständnis der Interaktionen zwischen simultanen Fang und Marktkräften ist von grundlegender Bedeutung in der Entwicklung von umfassenden Managementstrategien, die zusätzlich zu Nachhaltigkeitsaspekten auch die ökonomische Entwicklung berücksichtigen.

In Kapitel 5 wird ein neuer Ansatz zur Quantifizierung von Empfindlichkeit [sensitivity], Anpassungsfähigkeit [adaptive capacity] und Vulnerabilität [vulnerability] eines Akteurs auf einen bestimmten Treiber vorgestellt, basierend auf Ableitungen von Gleichungen die das Verhalten des Akteurs beschreiben. Dieser Ansatz wird auf das bioökonomische Modell aus Kapitel 4 angewendet. Die Ergebnisse zeigen, dass die Gewinne der Fischer am Empfindlichsten auf Veränderungen im Preis der Scholle, des Arbeitsgrenzertrags, die bestandsabhängige Fangeffektivität der Scholle, die Bestände der Scholle und der Gehälter reagieren. Diese Ergebnisse bieten eine breitere Entscheidungsgrundlage, wenn Managementstrategien zusätzlich zum Schutz der Bestände auch die Existenz der Fischerei als Ziel beinhalten.

Schließlich werden in Kapitel 6 die optimalen Fangmengen, basierend auf der Maximierung der inter-temporalen Wohlfahrtsfunktion der Haushalte, bestimmt. Diese Fangmengen hängen von allen beschriebenen Interaktionseffekten ab. Die Konsequenzen der Interaktionseffekte werden für ein Management mittels Quoten und mittels Steuern ermittelt. Während es auf den ersten Blick so scheint als ob ein quoten-basiertes Management nur Interaktionen innerhalb des Ökosystems berücksichtigen müsste, stelle ich fest, dass die Anreize der Fischer gegen eine Quote oder ein Rückwurfverbot zu verstoßen ebenfalls von Interaktionen im Fang und im Konsum abhängt. Sollen diese Anreize minimiert werden, so sind diese Interaktionen in der Gestaltung der Quote zu berücksichtigen.

Appendix B

Liste der aus der Dissertation hervorgegangenen Veröffentlichungen

B.1 Journalveröffentlichungen

Blanz, Benjamin (2019), "Modelling interactions of fish, fishers and consumers: Should bycatch be taken into account?" *Hydrobiologia*, 192–144.

Lauerburg, R.A.M., R. Diekmann, B. Blanz, K. Gee, H. Held, A. Kannen, C. Möllmann, W.N. Probst, H. Rambo, R. Cormier, and V. Stelzenmüller (2019), "Socio-ecological vulnerability to tipping points: A review of empirical approaches and their use for marine management." *Science of The Total Environment*, 47, 135838.

B.2 Konferenzveröffentlichungen

Blanz, Benjamin (2018), "Three types of interaction in multi-species fisheries and when they need to be considered." In *Proceedings of the 6th World Congress of Environmental and Resource Economists*, Gothenburg.

Quiroga, Emily and Benjamin Blanz (2021), "Vulnerabilities of a Socio-Ecological System Trough the Lens of a Bio-Economic Model." In *Proceedings of the 26th Annual Conference of the European Association of Environmental and Resource Economists.*

Appendix C

Erklärung

Hiermit erkläre ich, Benjamin Blanz, dass ich keine kommerzielle Promotionsberatung in Anspruch genommen habe. Die Arbeit wurde nicht schon einmal in einem früheren Promotionsverfahren angenommen oder als ungenügend beurteilt.

Ort/Datum Unterschrift

Appendix D

Eidesstattliche Versicherung

Ich, Benjamin Blanz, versichere an Eides statt, dass ich die Dissertation mit dem Titel “Optimal and Precautionary Management of the German Bight in the Presence of Thresholds” selbst und bei einer Zusammenarbeit mit anderen Wissenschaftlerinnen oder Wissenschaftlern gemäß den beigefügten Darlegungen nach § 6 Abs. 3 der Promotionsordnung der Fakultät für Wirtschafts- und Sozialwissenschaften vom 18. Januar 2017 verfasst habe. Andere als die angegebenen Hilfsmittel habe ich nicht benutzt.

Ort/Datum Unterschrift

Appendix E

Selbstdeklaration bei kumulativen Promotionen

Konzeption / Planung: Formulierung des grundlegenden wissenschaftlichen Problems, basierend auf bisher unbeantworteten theoretischen Fragestellungen inklusive der Zusammenfassung der generellen Fragen, die anhand von Analysen oder Experimenten / Untersuchungen beantwortbar sind. Planung der Experimente / Analysen und Formulierung der methodischen Vorgehensweise, inklusive Wahl der Methode und unabhängige methodologische Entwicklung.
Durchführung: Grad der Einbindung in die konkreten Untersuchungen bzw. Analysen.
Manuskripterstellung: Präsentation, Interpretation und Diskussion der erzielten Ergebnisse in Form eines wissenschaftlichen Artikels.
Für mindestens einen der vorliegenden Artikel liegt die Eigenleistung bei 100%.

Für den Artikel "A fisheries social-ecological system at risk of losing its capacity to adapt to global change" liegt die Eigenleistung für

das Konzept / die Planung bei	5%
die Durchführung bei	10%
die Manuskripterstellung bei	5%

Für den Artikel "Socio-Ecological Vulnerabilities to Tipping Points: A review" liegt die Eigenleistung für

das Konzept / die Planung bei	15%
die Durchführung bei	10%
die Manuskripterstellung bei	15%

Für den Artikel “Interaction Effects in Fisheries” liegt die Eigenleistung für

das Konzept / die Planung bei	100%
die Durchführung bei	100%
die Manuskripterstellung bei	100%

Für den Artikel “ Vulnerablity of a Socio-Ecological System” liegt die Eigenleistung für

das Konzept / die Planung bei	75%
die Durchführung bei	50%
die Manuskripterstellung bei	25%

Für den Artikel “Optimal Management of Fisheries with Interaction Effects” liegt die Eigenleistung für

das Konzept / die Planung bei	100%
die Durchführung bei	100%
die Manuskripterstellung bei	100%

Die vorliegende Einschätzung in Prozent über die von mir erbrachte Eigenleistung wurde mit den am Artikel beteiligten Koautoren einvernehmlich abgestimmt.

Ort/Datum Unterschrift